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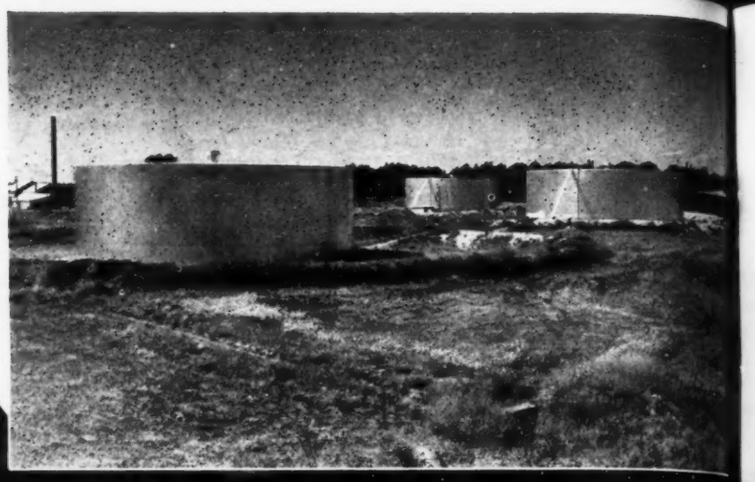

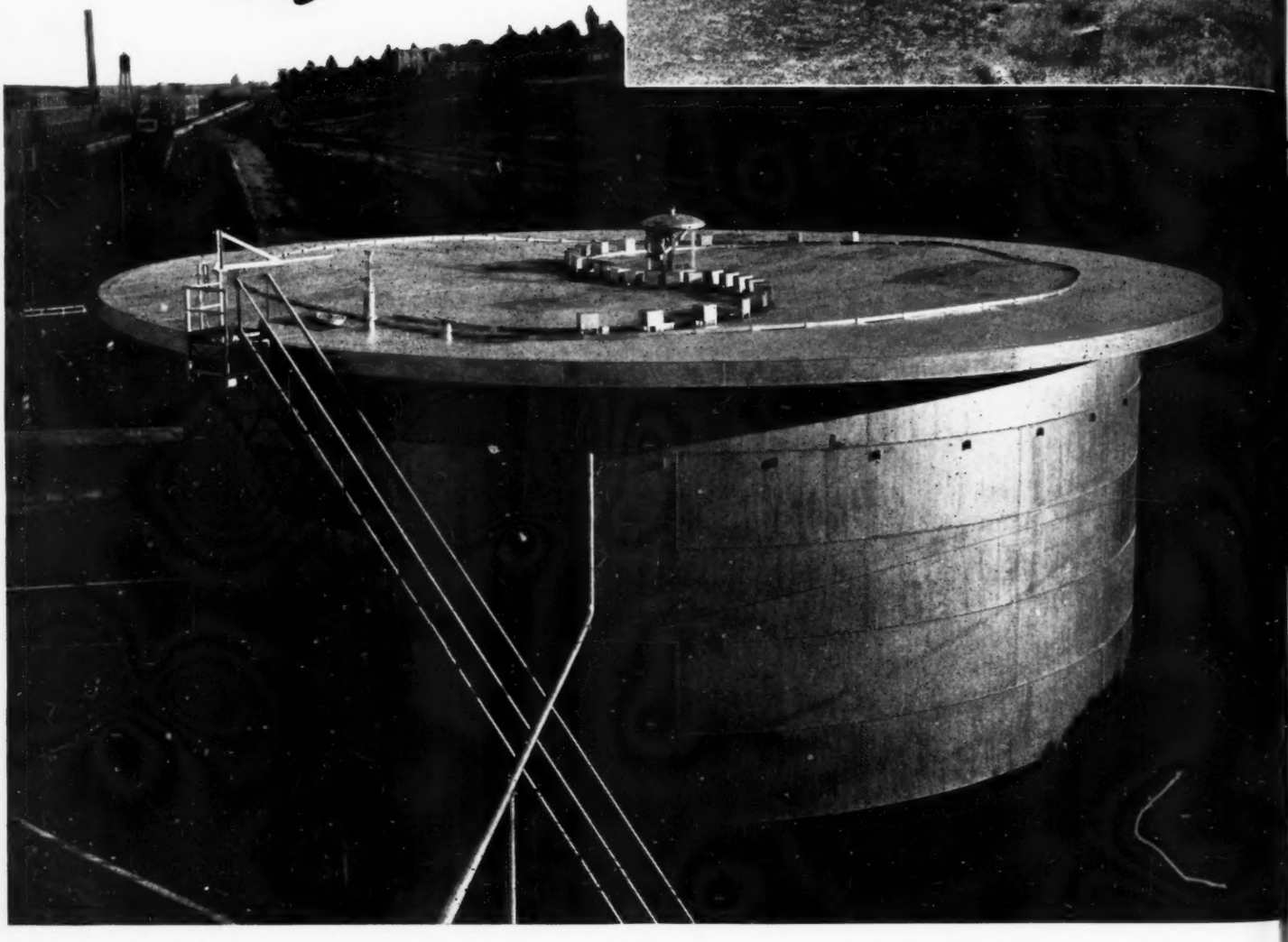

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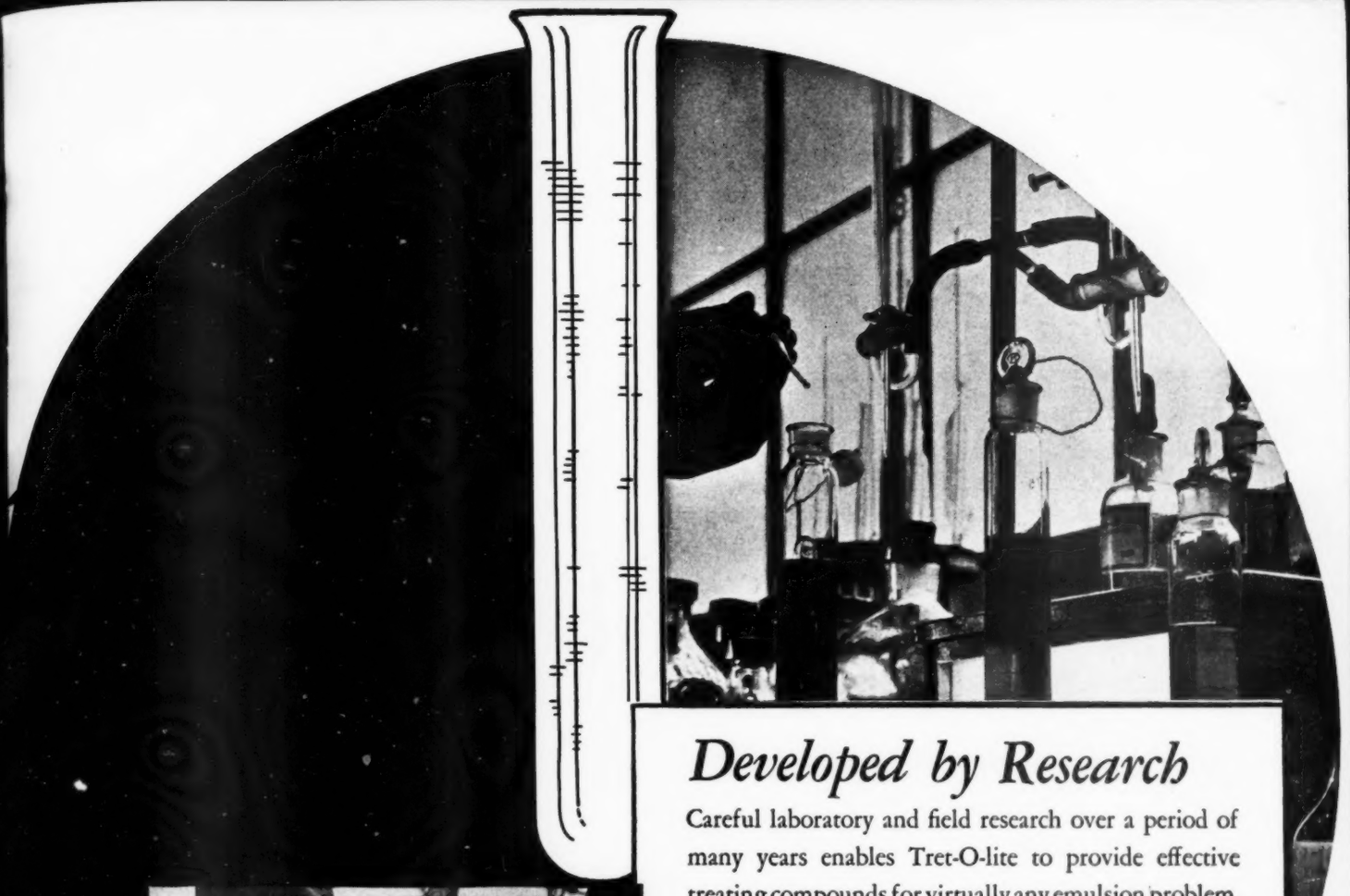

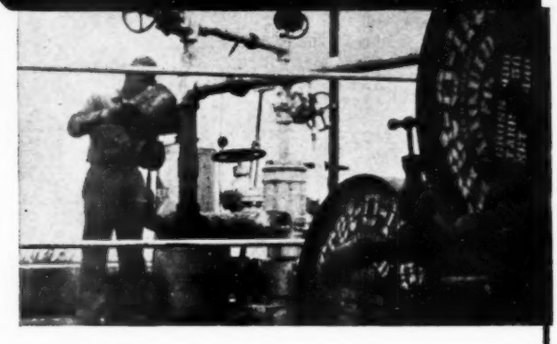

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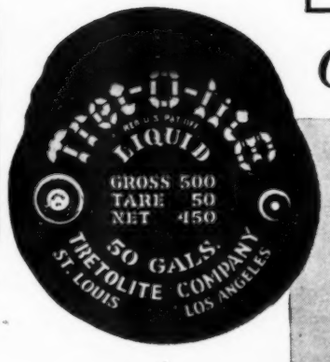

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THE Petroleum Engineer

VOL. XIV No.10

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A Magazine of Methods for Operating Men

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THE Petroleum Engineer

REFERENCE ANNUAL

The S. P. Dipmeter*

By H. G. DOLL

Director of Research, Schlumberger Well Surveying Corporation

THE problem of determining the angle and direction of the dip of the strata traversed by a bore-hole is of practical interest, and sometimes of vital importance—that does not have to be emphasized to the oil industry. The need for this type of information has existed ever since wells have been drilled. It has certainly not subsided, in spite of the numerous inventions and improvements made in other sectors of the drill-hole exploration science. The few examples given in this paper are but an illustration of this fact.

In the past, methods have been devised, and used, to solve this problem, but they have generally met with limited success, possibly because they more or less failed to answer the requirements of a modern age for fast, yet accurate measurements. If accurate, the results were obtained at the cost of very tedious and lengthy operations.

The new "S. P. Dipmeter" service now offered to the oil industry is the result of exhaustive research in this particular field. One might recall that in 1932 a dipmeter and electromagnetic teleclinometer service was made available. The apparatuses employed then were of a rather delicate and costly construction, and the measurements had to be made with precautions sometimes difficult to procure on the rig. Although the information given by the electromagnetic dipmeter was limited to the direction of the dip, very interesting results were obtained, in California, Trinidad, Venezuela, Roumania, and most notably in the Netherland East Indies.[1]

*Presented before American Institute of Mining and Metallurgical Engineers, Austin, Texas, October, 1942.

[1]1. "Electrical Coring; A Method of Determining Bottom-hole Data by Electrical Measurements," C. and M. Schlumberger and E. G. Leonardon. *A.I.M.E. Transactions*, Volume 110. New York Meeting, February, 1932.

2. "The Electromagnetic Teleclinometer and Dipmeter," C. and M. Schlumberger and H. G. Doll, World Petroleum Congress, London, July, 1933.

3. "The Electromagnetic Dipmeter and the Determination of the Direction of the Dip of the Sedimentary Strata Cross-cut by Drillings," C. and M. Schlumberger and H. G. Doll, International Congress of Mines, Metallurgy and Geological Technology, Paris, October, 1935.

4. "Discussion of Results Obtained with the Electromagnetic Dipmeter on a Known Geologic Structure," M. Schlumberger and H. G. Doll, Second World Petroleum Congress, Paris, June, 1937.

As is the custom in the July 1 issue of *The Petroleum Engineer*, regular editorial features, such as "Continuous Tables," "Highlights in Oildom," "Laugh With Barney," etc., are omitted. This issue is the Reference Annual, which is devoted only to papers of high reference value. The regular features will appear as usual in the regular July (15th) issue and in each issue thereafter.

The S. P. Dipmeter surveys present none of the drawbacks mentioned above: the apparatuses are rugged, free from constructional complications, therefore well adapted to field use. This, combined with the new, basically simple approach of the problem, explains the rapidity of execution of the measurements. The results are remarkably accurate and they are complete, giving the dip angle as well as the dip direction. As these surveys have already made quite a headway in field practice since their recent launching, it seemed timely to offer a brief description of the apparatus and method involved. In the light of the results actually obtained, some of which are included in this paper, an attempt is also made to visualize some of the far-reaching possibilities of this new development.

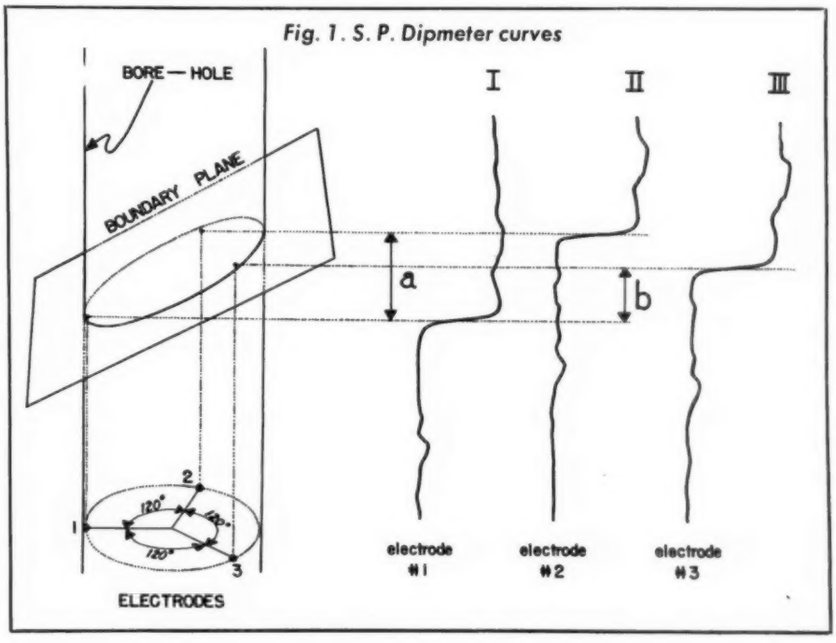
Dip Determinations

Dip determinations are often made by geologists in a general way by taking electrical logs in at least three wells not in a straight line and by establishing correlation between the logs. The correlation lines passing through the same formations in the three wells define the plane of the formations; hence the average dip is ascertained. Of course, this method discounts the possibility of geological disturbances occurring between the wells; besides, the main practical drawback of the method is that three logs should be available, i.e., three wells must have been drilled and logged.

The S. P. Dipmeter[2] utilizes a some-

[2]U. S. Patent No. 2,176,169.

Fig. 1. S. P. Dipmeter curves



what similar idea, but it requires only one well in which the three logs are simultaneously recorded. The measurements are made by means of three independent electrodes, 1, 2, and 3, spaced at 120° angles in a plane perpendicular to the axis of the instrument (and of the hole), and situated on a circle of a known diameter corresponding to that of the hole, so that the electrodes are always in fairly close contact with the walls of the hole (Fig. 1). The orientation of the electrodes is given by a photoclinometer, another purpose of which is to disclose the inclination and orientation of the drill-hole at the point of location of the instrument. The photoclinometer is thus an indispensable complement of the dipmeter.

The logs recorded by the three electrodes permit, as will be shown in more detail hereafter, accurately determining in the uncased part of the drill-hole three points of the boundary plane separating two beds of different natures, for instance, a porous bed and a non-porous one. These three points, being oriented by the photoclinometer, suffice to determine completely the plane in question.

The great accuracy that is necessary in view of the short distances between

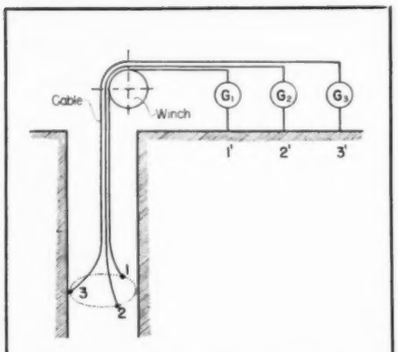


Fig. 3. Potential-measuring device

electrodes is procured through the simultaneous recording of the three logs and through the fixity of the relative positions of the electrodes and of the orienting apparatus.

In practice the electrodes are little disks mounted on three resilient supports, which in turn are mounted on a rigid elongated body; the supports also serve as guides for the instrument and keep its orientation practically constant when it is moved in the hole (Fig. 2). Each of the electrodes is connected through an insulated conductor to a separate potential measuring device at the surface of the earth, its circuit being closed through the earth and a ground electrode (Fig. 3).

Generally on top of the dipmeter (Fig. 2), and always in the same relative orientation, is placed the photoclinometer. This instrument, already well known in the industry, combines in one body a compass-needle and a clinometer consisting of a ball free to settle in equilibrium position on a graduated glass of known curvature. In that same body is a camera capable of taking pictures of the needle and of the ball. On the picture also appears a marker showing the orientation of electrode 1, which we may call reference electrode (Fig. 4).

The photoclinometer purposely is made long, and it also has centering guides, so that its axis practically coincides with that of the hole. The position of the clinometer ball is therefore a measure of the inclination of the well, and the compass-needle gives the bearing of that inclination. These two elements permit determining the correction that is to be made on the dip as measured by the S. P. Dipmeter proper.

The surface equipment comprises one control-panel box of small dimensions (Fig. 5), containing the switches and dials and instrument controls that govern, entirely from the surface, the taking of the photoclinometer pictures, and the operation of the S. P. Dipmeter. The galvanometers and the film of the recorder used for the standard electrical surveys serve for the recording of the S. P. Dipmeter logs. Connections between the control-box and the cable-winch, on the one hand, and the galvanometers, on the other hand, are of the instantaneous type.

Operation of S. P. Dipmeter

The operation of the S. P. Dipmeter is based on a now well known phenomenon, namely, the fact that the S. P., or Spontaneous Potential, measured by an electrode in the uncased part of a well varies in an abrupt manner when that electrode traverses the boundary plane that separates a porous stratum from a non-porous one. The phenomenon is being recorded simultaneously but independently, as said before, by the three electrodes of the dipmeter, which for that purpose is made to travel along the hole and to traverse the boundary plane in question. The three separate S. P. logs thus recorded —preferably at a very large depth scale —will be found of course to be substantially alike, but they are different in one important respect: the abrupt changes corresponding to the passage of the electrodes from the non-porous bed to the porous bed (or vice versa), do not inscribe themselves at exactly the same depth. The discrepancies in depth observed precisely correspond to, and are a measure of, the dip of the boundary plane separating the two beds, and consequently of the beds themselves.

It should be clear that other characteristics of the formations capable of showing a clearly distinguishable change when a change in formation occurs could be used instead of the S. P. for such determinations. For instance, one might well conceive a "Resistivity Dipmeter."

To go back to Fig. 1, we obtain three S. P. logs as shown on the right-hand side, and the discrepancies in depth (a) between reference electrode 1 and elec-

Fig. 2. S. P. Dipmeter assembly

TABLE I

Sta. No.	Depths, ft.	Azimuth well F. M. N.	Well drift	Orient. elect. No. 1 F. M. N.	S. P. curves			Angle of dip	Direction formation dip	
					I	II	III		F. M. N.	F. G. N.*
A	9440 9470	156°	5°20′	136°	x	D5.0″	D9.8″	54°	N 19° W	N 25° W

*From Geographic North. The magnetic declination in this case is 6° East.

trode 2, and (b) between electrodes 1 and 3, can be measured. If the well is strictly vertical, the knowledge of: the diameter of the circle on which the electrodes are situated, the quantities (a) and (b) and finally the orientation or bearing of electrode 1, as revealed by the photoclinometer picture, permits of an immediate and very simple determination of the dip angle and bearing of the boundary plane.

In the majority of cases the well is not vertical and the determination of the boundary plane is not quite so simple; allowance has then to be made for the inclination and orientation of the well. The determination is nevertheless very rapid, either through pure geometrical construction or through computation.

Interpreting Measurements

A special apparatus (Fig. 6) has been designed[3] that permits making a physical reconstruction of the elements found in the drill hole at the level under consideration. By means of the apparatus, the measurements obtained can easily and quickly be translated into terms of dip angle and direction of dip.

In practice, the survey of a horizon follows a series of simple steps, which may be briefly described: the dipmeter-photoclinometer assembly is lowered down the hole until it is some distance (10 to 15 ft.) below the desired section. The S. P. has been observed all the way down so as to make sure of the movement of the instrument. The latter is then pulled up to about 3 ft. below the section and stopped there. After a short interval of time to allow the instrument to settle, a picture is taken by the photoclinometer. This done, the section is surveyed by the three dipmeter electrodes. At the upper end of the section, a second photoclinometer picture is taken, which (besides giving the orientation and inclination of the well at that point) permits the operator to check whether the assembly has rotated while being pulled up. The instrument is then lowered below the section, and all the above steps and measurements are repeated in the same order.

Of course, generally, not just one horizon is being studied, and a S. P. Dipmeter survey will comprise a series of as many S. P. logs and photoclinometer determinations at as many levels as are deemed necessary to obtain the desired data.

[3]Developed by Owen H. Huston, Research Department, Schlumberger Well Surveying Corporation.

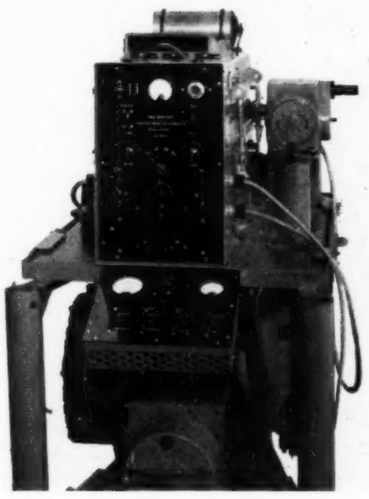


Fig. 5. Control panel and photographic recorder

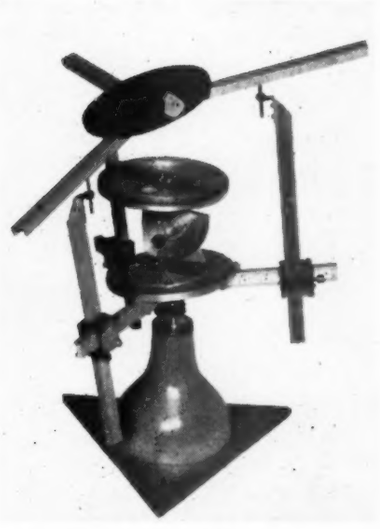


Fig. 6. Instrument for interpretation of measurements

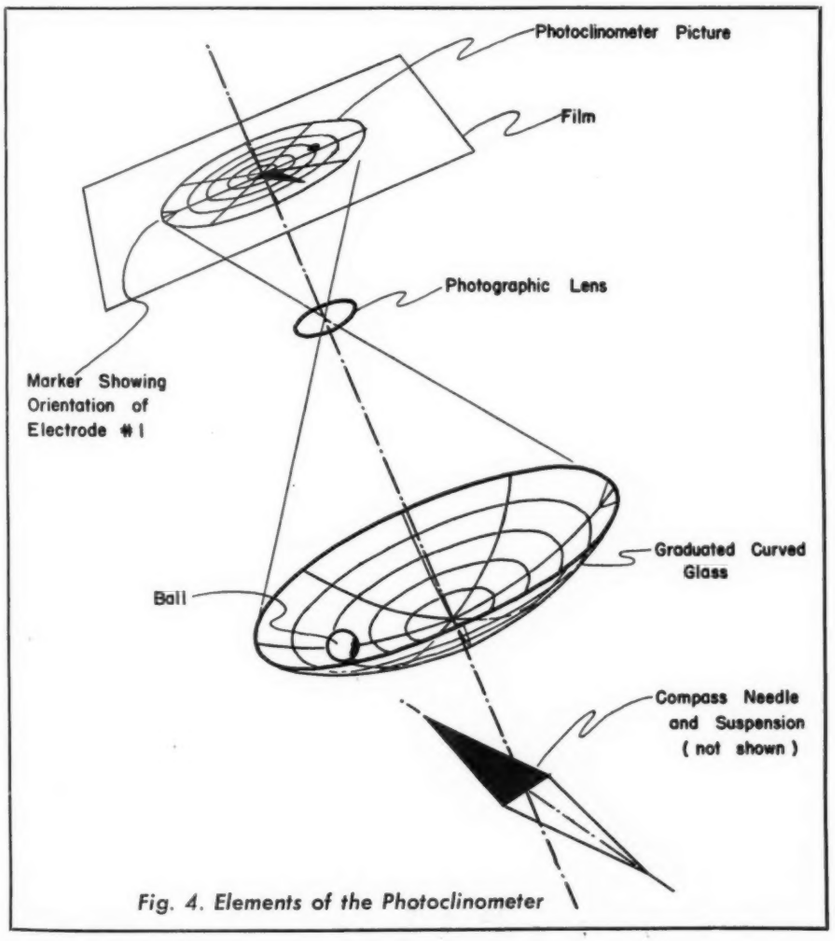


Fig. 4. Elements of the Photoclinometer

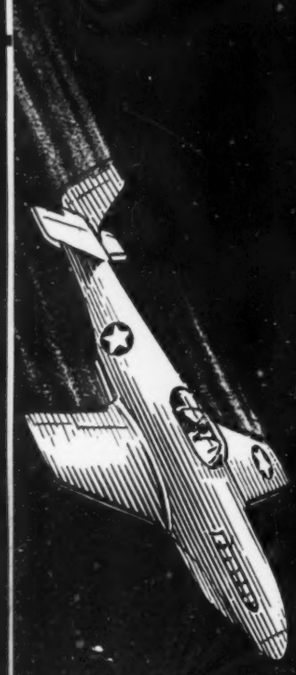
Results

The results as presented show for all the levels or stations studied: (1) the pictures of the photoclinometer, (2) the S. P. logs recorded by the three electrodes, (3) a table, which translates in figures the findings of the pictures and logs, showing on the one hand the elements of drift of the well (angle and bearing), and on the other hand, the elements of the dip, corrected to vertical (angle and bearing).

In Example A (diameter of hole, 9⅞ in), the photoclinometer was equipped with a clinometer glass capable of measuring drift angles up to a maximum of 15°. The pictures of the

(Continued on Page 22)

PULL OUT OF IT, SKIPPER...



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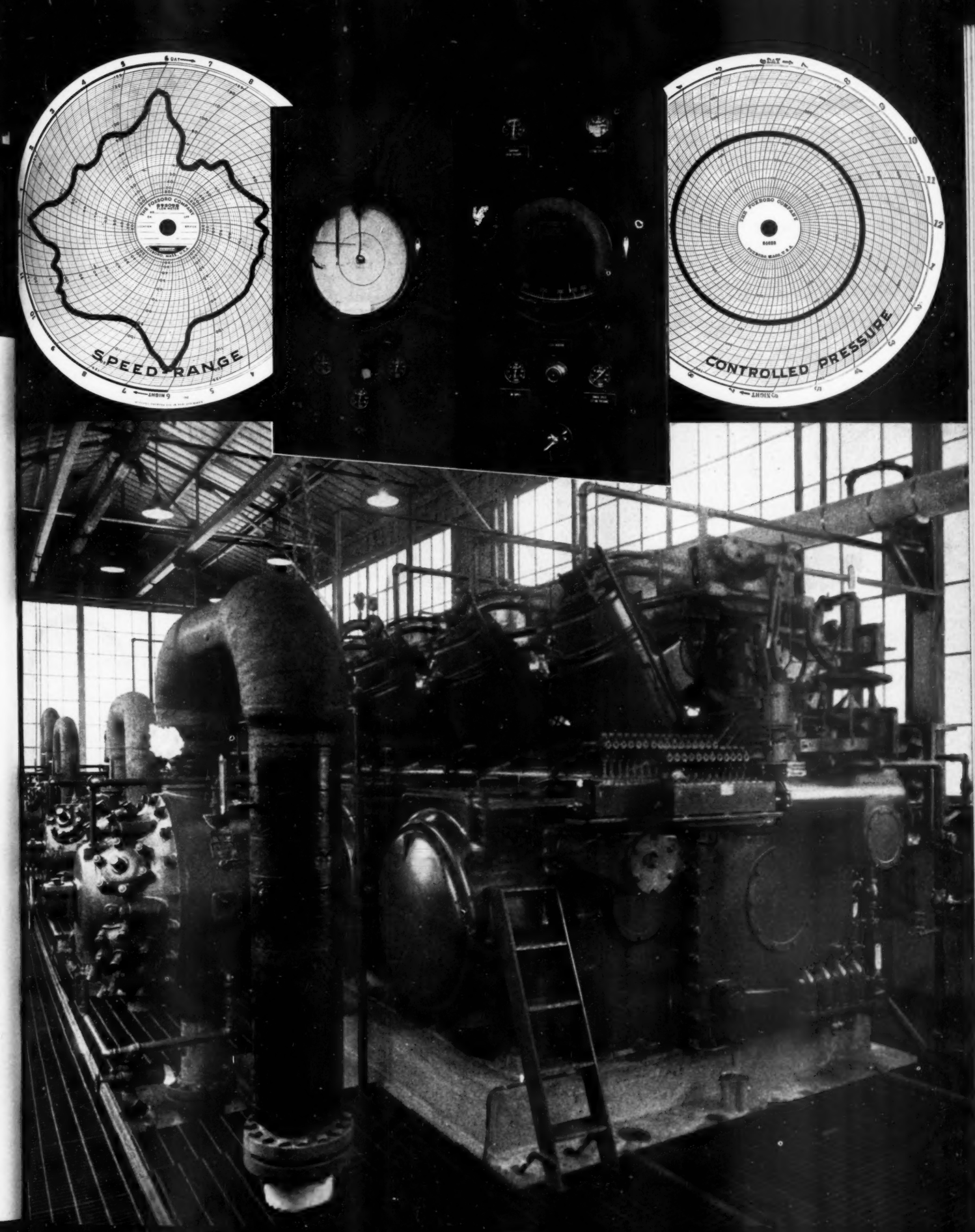

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TABLE 2

Sta. No.	Depths, ft.	Azimuth well F. M. N.	Well drift	Orient. elect. No. 1 F. M. N.	S. P. curves			Angle of dip	Direction formation dip	
					I	II	III		F. M. N.	F. G. N.
A	10630 10600	327°	3°	258°	x	U 3″	U 3″	21°	254°	261°

(Continued from Page 19)

ball and compass-needle (Fig. 7), projected on a screen, reveal that the average drift of the well in the section considered—9440 to 9470 ft.—is 5° 20′, and the azimuth of this drift, from the magnetic north, is found to be 156°. Furthermore, the pictures reveal that electrode 1, and consequently the assembly, have rotated by about 2° while the assembly was pulled up from 9470 to 9440 ft., which is quite satisfactory; the average orientation of electrode 1 is measured to be 136° from the magnetic north.

Coming next to a study of the logs (Fig. 8A), of which two transparent copies should be available, one tries to obtain the best superimposition of curves II and III (electrodes 2 and 3, respectively) on curve I, which is taken as reference curve. This result is achieved after a certain amount of shifting, the value and direction of which are noted. In the case at hand, curve II had to be shifted up by 5.0″ to superimpose on I; this means that electrode 2 recorded the change in formation 5.0″ before electrode 1 did; therefore, the strata were dipping down from electrode 1 toward electrode 2. This is reported in the column corresponding to curve II as D 5.0″ (see Table I). Similarly, the strata are found to dip down from electrode 1 to electrode 3 by 9.8″. From all the above elements, it is possible to find the value of the dip and its direction by geometric construction or with the help of the apparatus shown on Fig. 6. The direction can be reported either as 341° (clockwise from magnetic north), or N 19 W (19° from magnetic north in the west quadrant).

All the above information is summarized in the form of a table (see Table I).

In Example B (diameter of hole, 9⅞ in.), the discrepancies in depth between the curves II and III, on the one hand, and curve I, on the other, happen to be the same and equal to 3″; as to direction, the strata ascend or go up from electrode 1 toward electrodes 2 and 3 (Fig. 8B). This is reported accordingly in Table 2 by the notation U 3″.

In the two examples, the discrepancies in depth, and consequently the dip, could be measured with a great degree of accuracy, mostly because the dip was important enough to make these discrepancies large, partly also because the changes in the curves were fairly sharp. When the dip is much smaller, of course, a correct measurement of the absolute values of the discrepancies may become difficult, but a correct estimate of the sign of these discrepancies is almost always possible; in other words, for very small dips, the angle of dip cannot be given for certain, but its general orientation can.

It can readily be seen that the accuracy of the measurements will vary according to the value of the dip angle, the sharpness of the breaks in the recorded curves, and the size of the dipmeter apparatus, which depends on the hole diameter. Under normal conditions in the Gulf Coast territory, it has been found that the accuracy is very good for dip angles of 10° or above; between 5° and 10° reliable determinations can be made when other conditions are favorable; around 5° it is sometimes possible to give the general direction of the dip. Fortunately, it often happens that less accurate and less complete information is required from dip-measurements in the case of low dips than for steep ones. This fact is substantiated by the following discussion of the possibilities and practicable applications of the instrument.

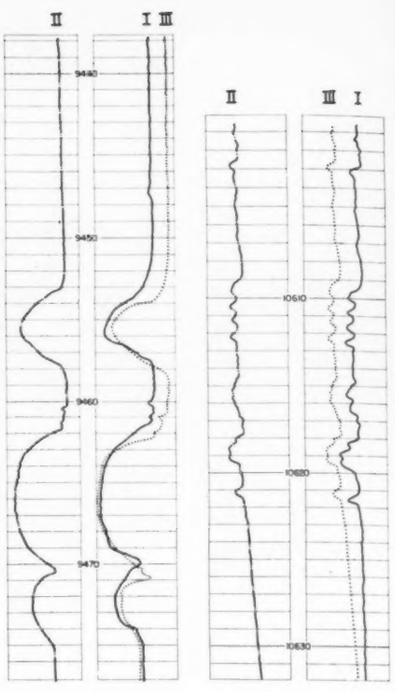

Fig. 8. S. P. Dipmeter curves

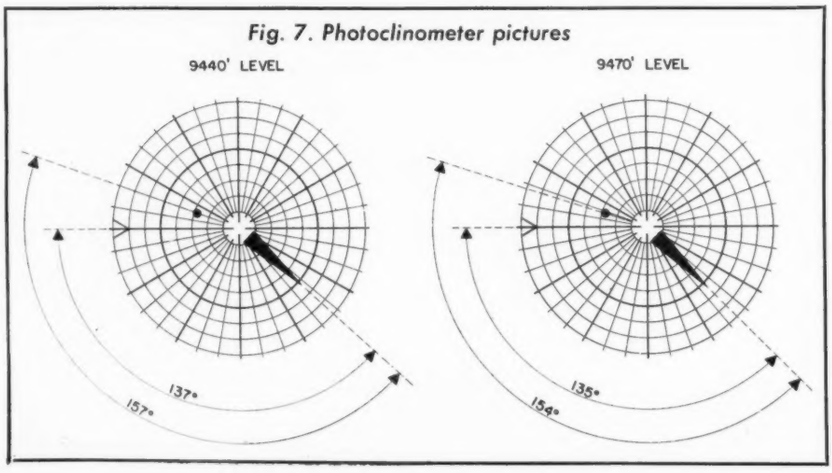

Fig. 7. Photoclinometer pictures

Applications of Instrument

This paper does not intend to discuss in detail the possibilities of dip measurements in oil-field practice. It is well known that dip determinations are of valuable assistance when drilling all types of geological structures favorable to oil accumulation, from the familiar types of anticlines and domes to monoclines, faults, unconformities, etc. It should be kept in mind, however, that the use of the S. P. Dipmeter offers some new possibilities heretofore practically impossible to attain.

With the new apparatus, dip determinations can be made at any level in an open hole after it has been drilled, regardless of whether cores are available. The S. P. Dipmeter survey can be performed at the time the electrical log is taken, the information thus obtained naturally supplementing the information given by resistivity and S. P. measurements. This is obviously a convenient and a relatively cheap way to have quickly data that could only be

SCHLUMBERGER DIPMETER

QUICK, ACCURATE DETERMINATION OF DIRECTION AND VALUE OF FORMATION DIP

With the same high degree of accuracy that has distinguished Schlumberger Electrical Well Logging, you may now determine formation dip and direction values. This new service combines two proven Schlumberger operations — electrical well logging and photoclinometer directional surveys. The instruments are lowered into the

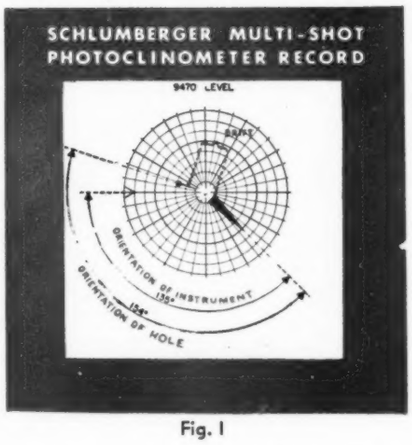

Fig. 1

hole on a standard Schlumberger cable, requiring only one trip in the well for the entire Dipmeter Survey. Simultaneous recordings are made of the drift and orientation of the well bore, the orientation of the instruments, and of 3 S.P. curves of the formation being investigated. Upon obtaining these data, the precise direction and magnitude of the formation dip can be easily determined with the aid of computing apparatus developed by Schlumberger.

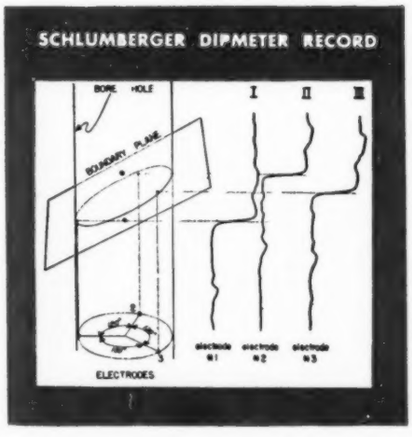

Fig. 2

Figures Nos. 1, 2 and 3 briefly outline the operations involved in a Dipmeter Survey:

The Photoclinometer record, Figure 1, which is obtained at the same time the Dipmeter is lowered into the hole, registers the drift angle of the hole, direction of drift, and orientation of the photoclinometer instrument.

The Dipmeter is an adaptation of Schlumberger electrical logging. Three electrodes spaced 120 degrees apart in a plane perpendicular to the axis of the instrument and located on a circle of a known diameter corresponding to the diameter of the hole, Figure 2, record three S.P. logs along three oriented generatrices in the hole. The shift in depths, as revealed by the three curves, may be translated into dip value.

Fig. 3

The computing apparatus, Figure 3, eliminates the mathematical computation of formation dip values. Utilizing an adjustable plane table, compass, vernier and adjustable upright arms, which are perpendicular to the plane, it reconstructs, mechanically, the various operations performed by the Dipmeter in the hole and the direction and value of the formation dip is read directly from it.

SCHLUMBERGER

Originators of Electrical Well Logging

had during the drilling by means of mechanical cores cut and examined under special conditions.

Another point of great importance is the fact that numerous determinations can be made accurately in a short time and at many depths in a drill hole. Experience has shown that structures are usually more complicated than expected; geological cross-sections are often revised after many holes have been drilled. There is no doubt that a better knowledge of the dip at the time the first few wells are drilled would greatly help in the future drilling program, giving to the geologist and to the production engineer, in the first stage of development of a new field, a more complete picture of the conditions underground. By making dip measurements at relatively short intervals in the hole, it will be discovered in many cases that the dip angle or the dip direction changes with depth. This indication permits a better definition of the subterranean contours roughly outlined by geophysical means, with the certainty attainable only with measurements *in situ*, and an ease that leaves other methods far behind.

Just as important as the correct definition of subterranean contours, and a prerequisite to the evaluation of the oil reserves in a given field, is the determination of the true thickness of the producing horizon (or horizons). It will be obvious that in some structures (such as domes of the piercement type for instance), where steep dips must be expected, a correcting factor dependent upon the dip has to be applied to the apparent thickness given by the electrical logs or the driller's logs. The S. P. Dipmeter readily supplies this indispensable correcting factor.

When the first well of a new prospect happens to be a dry hole, the problem that confronts the development men is to determine in which direction to direct the side-track or to drill the next well. That question again is answered by the dipmeter. In the case of a side-track, the dip measurement will further help to select the side-track angle. This is illustrated for the case of a piercement type dome in Fig. 9. If the dip was found to be small, a little deviation of the original hole has a good chance to hit the oil, without hitting the salt dome. On the contrary if the dip is very important, the original hole will have to be deviated considerably. The same comments apply to the case, admittedly much less frequent, of oil occurring on the flanks of an intrusive volcanic neck.

If the operator is more fortunate, his first well being a producer, S. P. Dipmeter measurements, together with the production data, indicate where to set the next location, and in what direction the future field will develop. Of course, as pointed out earlier in this paper, the amount and accuracy of the information obtained from the strata are directly governed by their angle of dip. If the dip is large enough, it will be possible to answer all the questions above with great precision, and particularly to restrict the zone in which to drill the next well to a small fraction of a certain quadrant (Fig. 10). On the other hand, if the dip is very small, so as to render its accurate determination delusive, only the general direction of the next location, within a quadrant or so at worst, can be given. However scanty such information may seem, it is very precious indeed in wildcat territory, when all data at hand give such an incomplete picture of the structures.

Another application of the dipmeter, when the results already obtained are promising, is the identification of fault blocks. Not enough evidence on this complex subject is available yet, but S. P. Dipmeter measurements alone have made it possible in one field to locate three faults through the identification of the adjacent blocks in several wells, each block being distinguished from the others by the angle and the orientation of its dip.

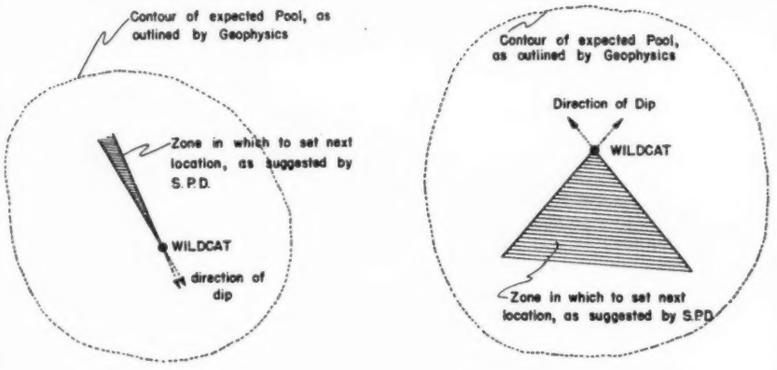
Contour of expected Pool, as outlined by Geophysics
Zone in which to set next location, as suggested by S.P.D.
WILDCAT
direction of dip
Contour of expected Pool, as outlined by Geophysics
Direction of Dip
WILDCAT
Zone in which to set next location, as suggested by S.P.D.
Case of steep dip
Case of very small dip

Fig. 10. Sectors in which to drill wells

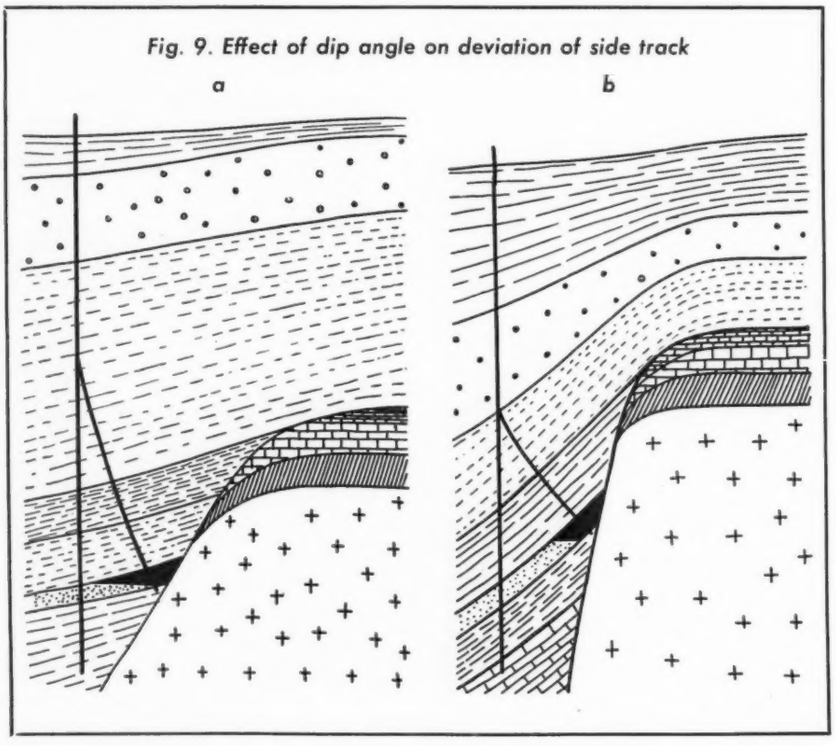

Fig. 9. Effect of dip angle on deviation of side track

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The Use of Electrode Spacing in Well Logging*

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APPLICATION of electric logs has been used in correlation of subsurface structure to determine the size and shape of the oil reservoir. Such a knowledge is hardly complete until saturation and productiveness are determined for the various horizons. It is difficult to use electric logs successfully for this purpose because of the many factors that influence the curves. In this work an effort was made to establish an empirical correlation between formation resistivity for a series of electric log curves and water saturation and oil productivity of sand. Electric logs were obtained by recording with 10 different electrode spacings through the same interval of a well. In the analysis of these curves all factors except two, a dependent and an independent variable, were held constant. The interval studied had been cored and a large number of samples were analyzed in the core laboratory in order to compare the values of permeability and saturation with the measured values of formation resistivity. Results of this analysis indicate: First, the depth to which mud filtrate enters a sand body, second, a correlation between permeability and sand resistivity for shallow penetration depths, and third, that the water saturation for an oil sand can be determined from the measured sand resistivity after making suitable corrections for sand thickness. The procedure in the last method depends on a thickness factor correction and a theoretical curve. The accuracy of the theoretical curve is now being tested in the laboratory.

Introduction

In an effort to place the analysis of electric logs on a quantitative basis there is need for a better understanding of the many factors that influence an electric log curve. These factors may be large differences in sand thickness, permeability of the sand, salinity of the interstitial water, mud resistivity, formation temperature, etc. A number of examples were presented by Archie,[1] which treat the effect of sand thickness on measured resistivity. He compares the true resistivity of a sand with the observed resistivity for sands 8 ft., 16 ft., and 24 ft. thick, and finds the observed resistivity of the 8-ft. sand to be approximately 50 percent of the true resistivity. He also develops an equation involving the formation factor that is used to calculate water saturation in thick sand bodies.

In the present work the majority of the sands ranged from 1 to 10 ft. in thickness, with only one 30-ft. sand. All data were obtained from one well in the Rosecrans oil field, California. This variation in sand thickness is typical of the California producing horizons and no doubt accounts for the slow progress in the quantitative analysis of electric logs. The present study appears to lend itself to a statistical correlation because of the large number of thin sands cored and analyzed. Laboratory tests are still in progress to determine the accuracy of one curve presented in the report that relates the resistivity of a sand to the percent water saturation at several salinities.

On initiating the experimental runs electrode spacings were increased from 5 to 89 in. through a large number of increments in an effort to follow the change in measured resistivity to points beyond the distance mud filtrate would enter a sand body. In addition, the many thin sand bodies encountered during coring presented an opportunity of relating sand thickness to the measured resistivity.

Experimental Data

The well chosen for the experiment was cored continuously from 5550 to 6447 ft. At intervals in this operation it became necessary to stop the coring in order to ream the hole. The element of time from the start of coring at 5550 ft. to that of running the electric log amounted to 12 days, during which period the upper portion of the cored hole was subjected to 11 round trips of the bit, as compared to one round trip for the lower portion of the hole. Circulation of mud was continued four hours after the last core was taken, in order to insure a uniform conditioning of the mud.

Table 1 lists electrode spacings used in this electric log survey for a single potential and single pick-up device.

Fig. 1 illustrates the positions of the electrodes with respect to a simple voltage curve that might exist in a homogeneous formation. The present use of the term depth of penetration[2] referred to in Table 1 is a relative expression for comparing the effect of the electrode spacings. This expression determines an approximate distance in a homogeneous formation to a point at one-half the voltage between that of r (distance to the pick-up electrode No. 1) and that at r^1 (distance to a point of zero voltage No. 2). This can be expressed by:

$$\text{D. P.} \frac{2\,r\,r'}{r \div r'},$$

This equation gives a practical concept to the effect of electrode spacing that can be readily used for correlating.

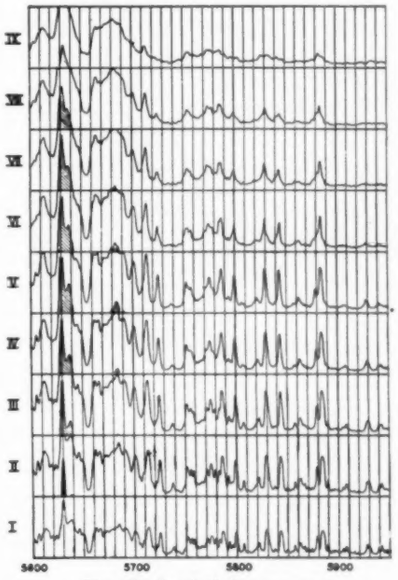


Fig. 2. Resistivity curves

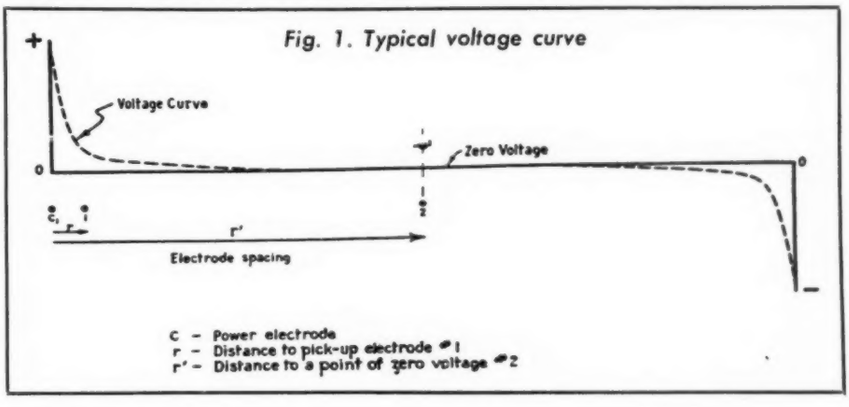


Fig. 1. Typical voltage curve

*Presented before American Institute of Mining and Metallurgical Engineers, Los Angeles, California, October 15 and 16.

[1]References are at the end of the paper.

TABLE 1

Electrode spacing and depth of penetration

Curve number	Electrode spacing r (in)	Electrode spacing r^1 (in)	Depth of penetration D.P. (ft.)
1	5	600	0.83
2	10	600	1.64
3	15	600	2.43
4	20	600	3.22
5	25	600	4.00
6	35	600	5.50
7	40	600	6.20
8	47	600	7.30
9	63	600	9.50
10	89	600	12.90

TABLE 2

At time of survey	On completion
Formation temperature, 188°F.	Prod. index, 1.0
Mud resistivity 4 ohms, mud temp. 77°F.	Static pressure, 300 lb.
Mud resistivity 2 ohms, mud temp. 160°F.	Gas-oil ratio, 3700
Mud loss, 4.3 cc. 5-15 min.	Initial cut, 37.0 percent
Mud weight, 76 lb. per cu. ft.	Salinity, 1575 gr. per gal.
Mud salinity, 35 gr. per gal.	

Table 2 lists pertinent data relative to the test. It should be noted that the mud temperature at 160°F. differs from the formation temperature of 188°F. This temperature difference is the result of circulating the mud previous to running the electric log survey. The salinity of the interstitial water was assumed to be the same as the salinity of the produced water, 1575 gr. per gal.

Curves corresponding to electrode spacings tabulated in Table 1 were arranged in Fig. 2 so that absolute values of resistivity could be measured at any depth.

As already explained, each curve is a measure of the formation resistivity using different penetration depths. The majority of the data used in the following correlations were obtained from Fig. 2 by measuring values of resistivity for a sand from the respective curves and repeating this procedure for all the sand bodies cored and analyzed. On plotting the value of sand resistivity for each electrode spacing with the corresponding depth of penetration, a typical curve was obtained (Fig. 3, Curve 1).

Resistivity-Penetration Data, Permeability Correlations

Point A in Fig. 3, Curve 1, is the resistivity of the mud corrected for temperature.[3] With greater depths of penetration the values of resistivity increase until (B) is reached. This increase in measured resistivity is due to the decreasing influence of low mud resistivity as a result of greater penetration depths, and also because the infiltration of fresh water has displaced some oil and diluted the salinity of the interstitial water. Infiltration of fresh water tends to increase the measured resistivity above the sand resistivity approximated by the value at C. Fig. 3, Curve 2, is a comparison to scale of the increase in resistivity with depth of penetration for a thin calcareous shell. In coring this interval there was some lost recovery of the shell and therefore its thickness was estimated from the electric log shallow penetration curve. The dotted line to the point D is an estimate of what would have been recorded for a shell of appreciable thickness, Fig. 3, Curve 2. The decrease in the measured for resistivity along E is due to an averaging with adjacent bodies having a lower resistivity. A more detailed discussion of the correction thickness will follow later. In Fig. 4, a number of resistivity-depth of penetration curves for sand bodies of varied thickness but having nearly the same

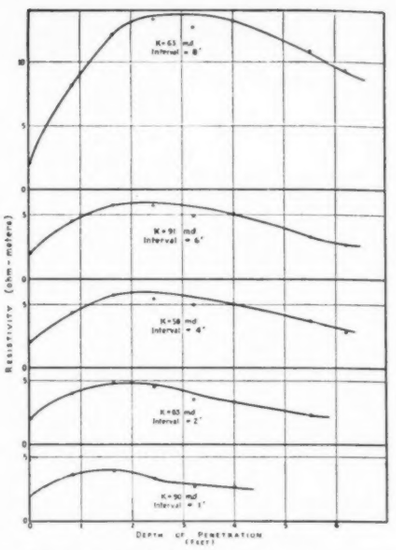


Fig. 4. Resistivity-depth of penetration curves for sand bodies

average permeability are plotted. It will be noted that the maximum position of resistivity on the curves shifts to shallower penetration depths for the thinner sand bodies. This shift is not a true measure of the relative penetration of the infiltrated fluid, but is again the averaging effect of adjacent bodies of lower resistivity. Decrease in resistivity of a thick sand as illustrated by Fig. 3, Curve 1, where the position of the peak on the penetration curve is less than one-half the thickness of the sand body, establishes the limits of penetration of the mud filtrate. This is because the sand body is so thick that the influence of adjacent bodies with low resistivity are of minor importance.

Fig. 4 is a plot of penetration curves for several sand bodies having comparable permeability and differing in sand thickness. At a common penetration the values of resistivity become increasingly large for the thicker sands. With permeability constant this would suggest that measured resistivity is a function of sand thickness. As interstitial water saturation is a function of permeability, as established by Schilthuis,[4] and resistivity is a function of saturation, measured resistivity is then a function of sand thickness and permeability. To establish these correlations it becomes necessary to keep one of the variables constant. In this analysis the sand thickness is held constant.

In Figs. 5 and 6 are illustrations of the scattering of points when using an electrode spacing of 5 in. and sand thickness of 0.75 and 6.8 ft.

Fig. 7 is a composite of this type of curve for all the sands considered. In the construction of the curves it appeared as if they converge to a point. A

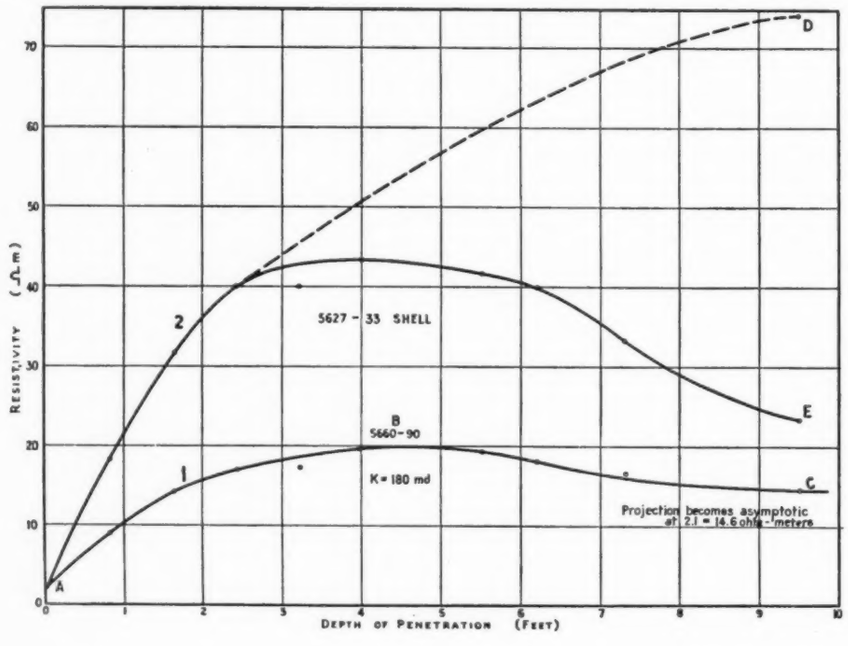


Fig. 3. Measured resistivity for a thick sand and a thin shell

permeability of 1 millidarcys and an average resistivity for 10 shale bodies of varied thickness was chosen as the point of convergence.

The permeabilities of the shales are not known so the curve could have ended at 0.1 millidarcys or 0.01 millidarcys. In either case this would cause little change in the curves at larger values of permeability. The regions of uncertainty are therefore drawn as broken lines. The average number of permeabilities obtained per plotted point were 1.07, 1.83, 2.72, and 4.4, respectively, for the sands 0.75, 2.1, 4, and 6.8 ft. thick. An arithmetic average was used in every case for determining the permeability. In a number of instances this included a very wide range of individual permeability values and it is believed that a portion of the scattering in Fig. 5 is due to an insufficient number of permeability values. To supply the present core analysis data, 286 samples were taken for the testing of permeability, porosity, and saturation. Therefore, another correlation was constructed using 20-in. electrode separation, commonly referred to in California as the normal electrode spacing, Fig. 8.

The measured resistivity value taken from the curves with this electrode spacing lies below the plotted trend on nearly all the restivity-penetration curves. It was therefore necessary to choose a value of resistivity from the trend rather than that measured. It became evident that a correlation with the 20-in. spacing would not be as good as that with the 5-in. spacing. This can best be illustrated by referring again to Fig. 4 where the values for 0.75-ft. and 2.1-ft. sands are chosen on the decreasing side of the resistivity curve whereas the value on the 8-ft. sand is taken from the peak of the curve.

The curve of the 4-ft. sand in both Figs. 7 and 8 lies too close to the 2-ft. sand. Original data on the 4-ft. sand did not correlate as well as the other sands and therefore its present position may be in error. A cross plot of the curves in Figs. 7 and 8 at constant permeability are shown in Figs. 9 and 10.

For a permeability of 180 millidarcys the curve was extended to 30 ft. Here again the points of the 4-ft. sand appear low. The trend of the 180-millidarcys curve influences the construction of the 50-millidarcys curve whereby little value is placed on the 4-ft. point. These curves illustrate the effect that thickness has on the measured resistivity of a sand. The increased slope of the curves with a 20-in. electrode spacing, as compared to the curves with a 5-in. electrode spacing, probably results from the greater influence of mud resistivity on the shallow 5-in. penetration curves.

It should be remembered that the curves for the 5-in. and 20-in. electrode spacings are made from electric log surveys in a single well. As the measured resistivities are for shallow penetrations the curves are subject to change through the effect of mud resistivity and size of the well bore. In the use of these curves consideration must be given these factors.

Calculating Water Saturation

So far this discussion has dealt largely with an analysis of the depth-penetration curves in the region of infiltration. To determine water saturation of large sand bodies from resistivity it is necessary to know the relation between sand resistivity and water saturation. A series of theoretical curves, Fig. 11, were constructed that offer this utility and are now being checked by laboratory tests. A formation factor was calculated for shales.

Measured resistivity of the intersti-

Fig. 5. Permeability-resistivity relation for 5-in. electrode spacing and average sand thicknesses of 0.75 ft.

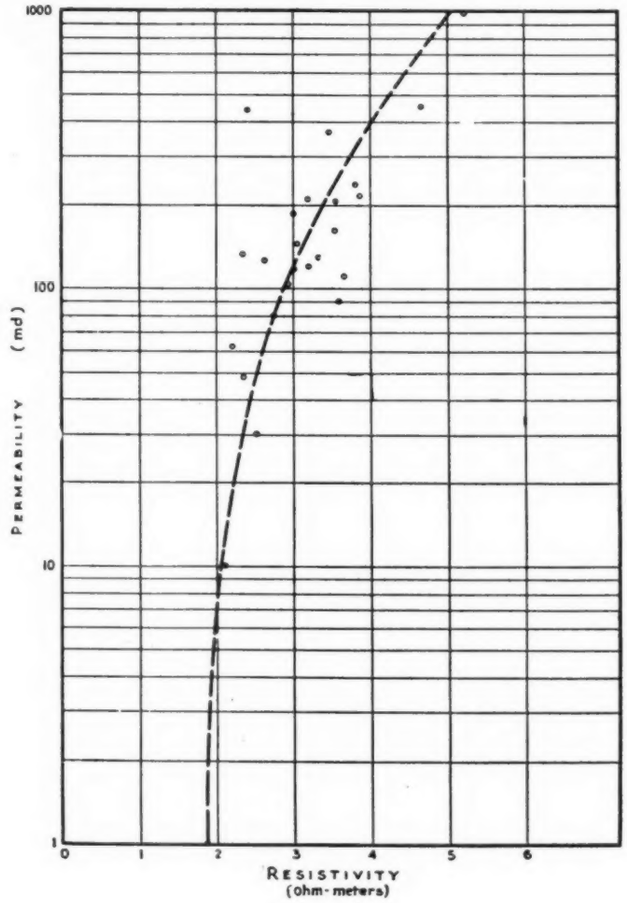
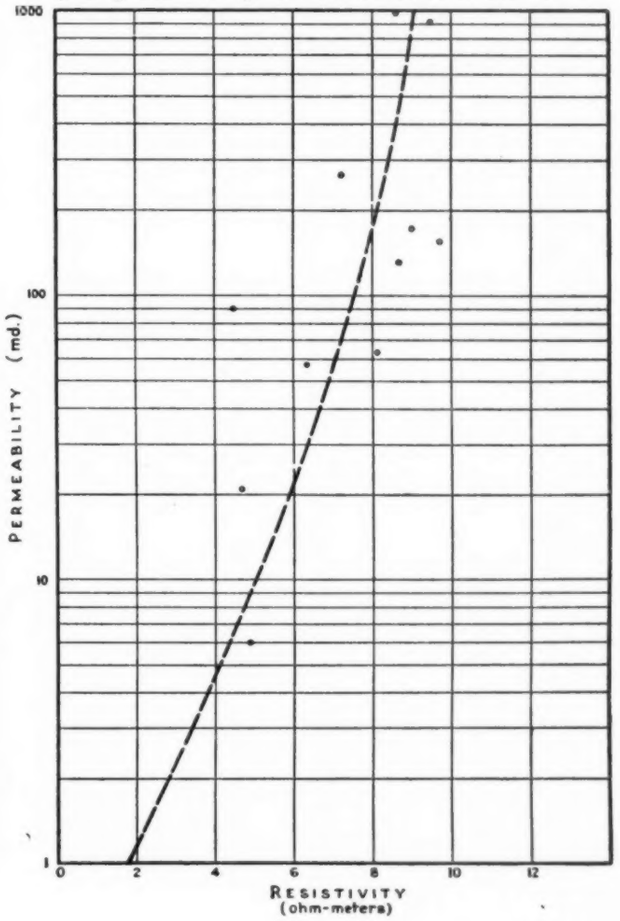


Fig. 6. Permeability-resistivity relation for 5-in. electrode spacing and average sand thicknesses of 6.8 ft.



$$F = \frac{\text{resistivity of shale (assumed 100 percent saturated)}}{\text{resistivity interstitial water}} = \frac{1.8}{0.105} = 17$$

tial water at 188°F. agrees closely with the calculated value. It was therefore possible to determine with accuracy the resistivity of water having salinities of 70, 150, 250, 500, 750, and 1000 gr. per gal. The values of resistivity for these salinities were multiplied by the formation factor, which gave the resistivity of a sand characterized by 25 percent porosity and 100 percent saturation. The trend of resistivity with saturation was then determined from the curves developed by Martin,[5] Jakosky,[6] Wyckoff,[7] and Leverett,[8] which relate the change in percent saturation of a sand to the percent of original conductivity at 100 percent saturation. Before applying the curves in Fig. 11 to the measured values of resistivity, it was necessary to devise an empirical curve that would correct the resistivity for thin sand bodies. A tentative curve was constructed with an average permeability of 180 millidarcys and an electrode spacing of 63 in. (Fig. 12).

Due to limited amount of data the curve has regions of approximation, but for the thinner sand bodies individual points are weighted values and line up on a smooth trend. A curve of thickness factor, Fig. 13, was constructed from Fig. 12.

It is assumed in this construction that the resistivity of the 30-ft. sand is correct and thickness factors determined for the thinner sands so the product of the measured resistivity times the thickness factor equals the true resistivity of the sand. It is believed that the thickness factor curve can be applied to sands of different permeability with reasonable accuracy. A trial solution was made for a number of cored sands for which the values of permeability were measured, Table 3. Calculations for saturations in Table 3 use the measured resistivity at a penetration of 9.5 ft.

Individual water saturation can be obtained by inserting the corrected resistivity on the 1575 gr. per gal. salinity curve in Fig. 11. These are the values listed as S_2 in Table 3. In order to weight the saturation values for the above eight sands it was necessary to

TABLE 3
Calculated saturation of eight sands

Sand thickness t (ft.)	Permeability K (millidarcys)	Critical saturation S_1 (percent)	Measured resistivity 9.5 ft. D.P.	Thickness factor T.F.	Corrected resistivity in ohms of the mud	Calculated saturation S_2 (percent)
30	180	24	14.6	1	14.6	34
7	977	21	14.35	2.8	40.2	20
5	173	24	4.0	3.6	14.4	34
6	131	26	4.66	3.15	14.7	33
6	91	27	1.8	3.15	5.66	54
7	63	29	5.34	2.8	15.0	33
10	263	23	5.06	2.06	10.4	40
9	57	30	4.0	2.26	9.1	43
	=18021	=4182				=5473

Percent interstitial water = $\frac{4182}{18021}$ = 23.2 percent

Percent calculated saturation = $\frac{5473}{18021}$ = 30.3 percent

Initial cut of well = 37 percent

Weighted saturation = $\frac{\Sigma tks}{\Sigma tk} \frac{346,083}{15,032}$ = 23.0 percent

Fig. 7. Permeability-resistivity relation for 5-in. electrode spacing and sand thicknesses of 0.75, 2.1, 4.0, 6.8 ft.

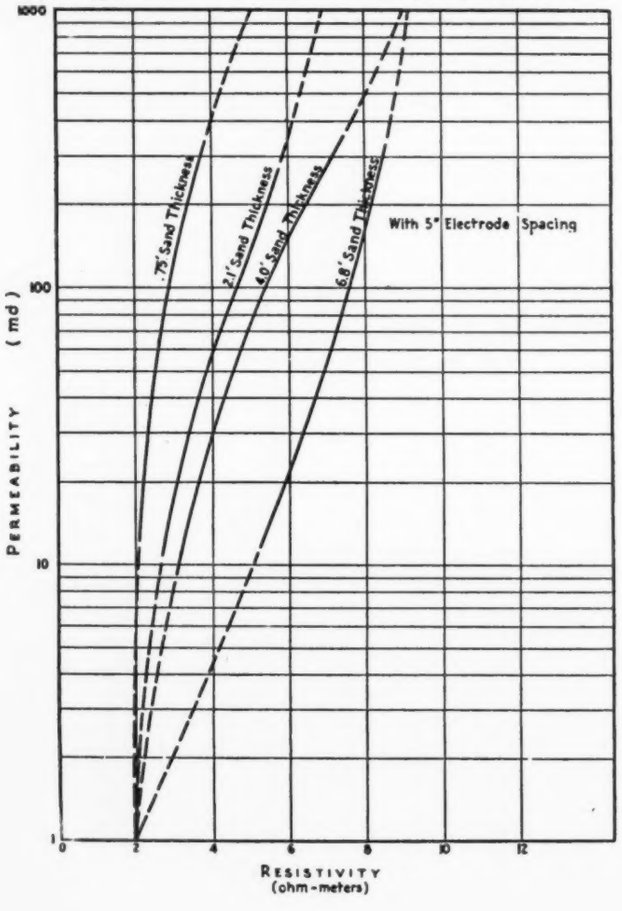
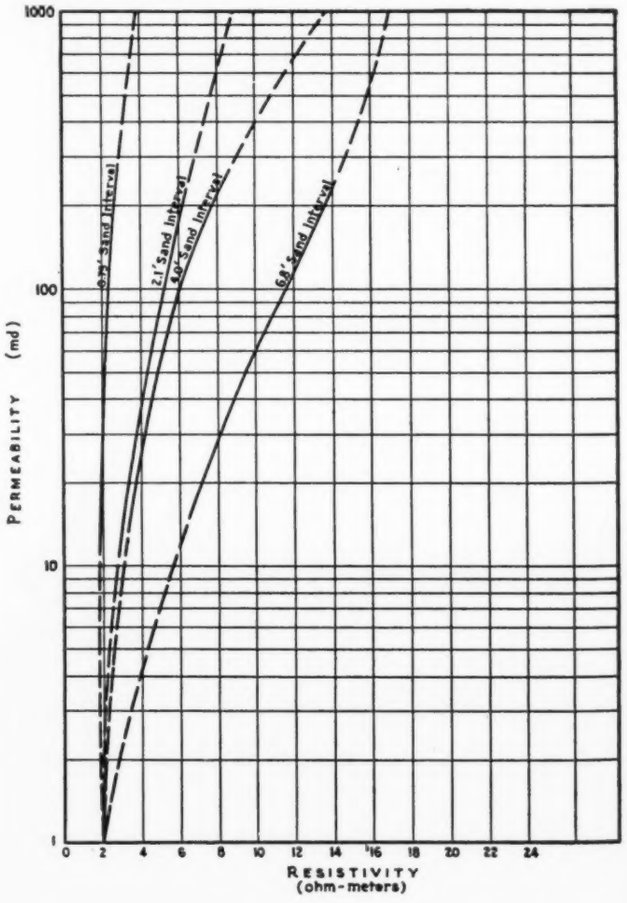


Fig. 8. Permeability-resistivity relation for 20-in. electrode spacing and sand thicknesses of 0.75, 2.1, 4.0, 6.8 ft.



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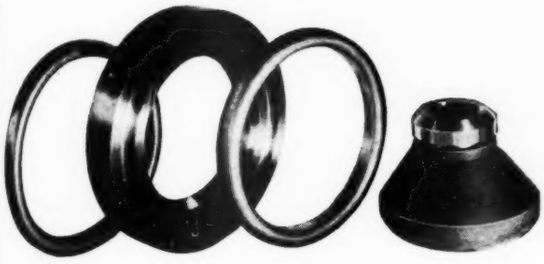

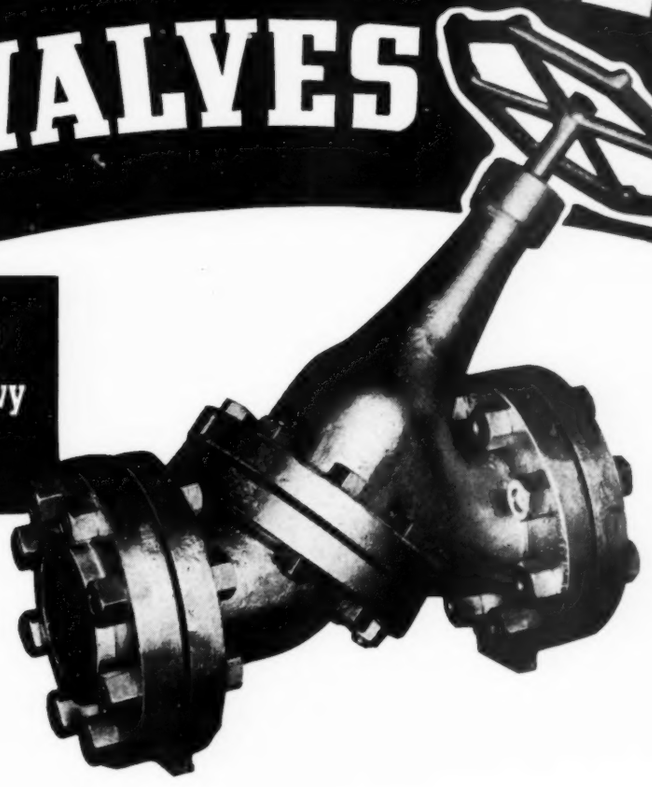

Hunt standard All Steel Line Valves, the valve that has established records for longer life, lower costs and minimum trouble, now have as a companion the Hunt Heavy Duty Series for higher pressures. This new series valve is available in 2- and 4-inch, 4,000 and 6,000 pounds test range.

The secret of the Hunt Heavy Duty Valves' dependability and economy is the reversible disc and seat which gives double the life of ordinary valves. The seat is held in place by two standard API rings. Being of lower brinell hardness than the disc, these rings take the wear, assuring positive seal as the disc and seat wear.

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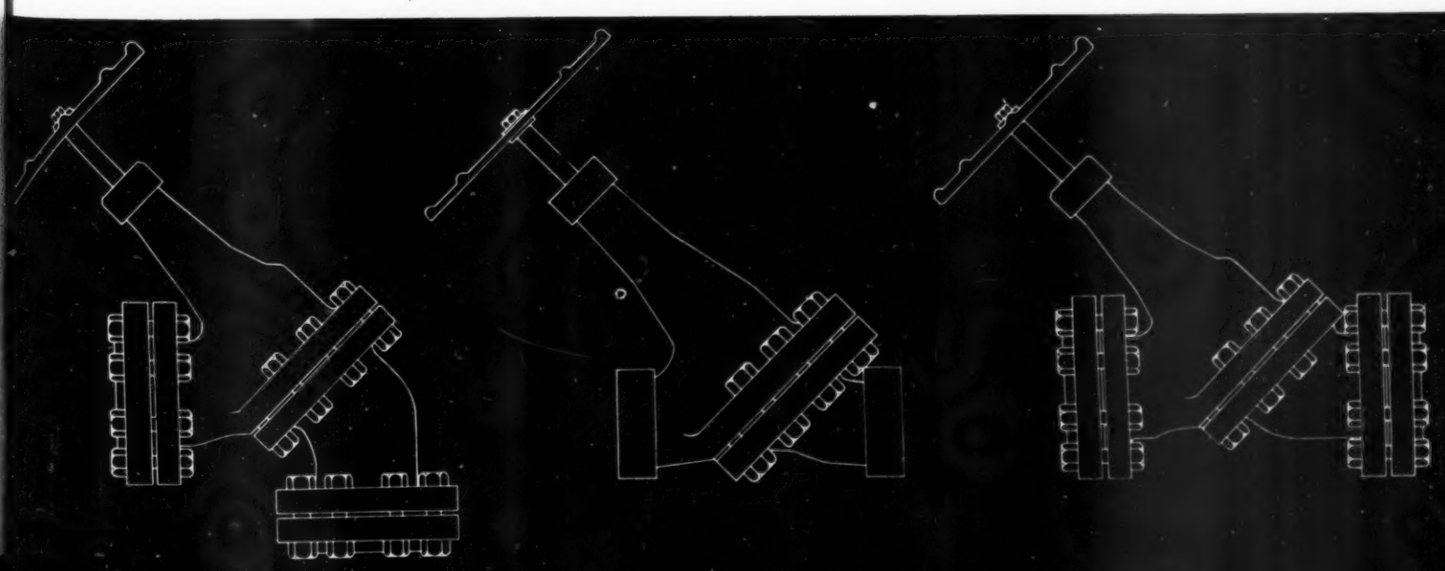

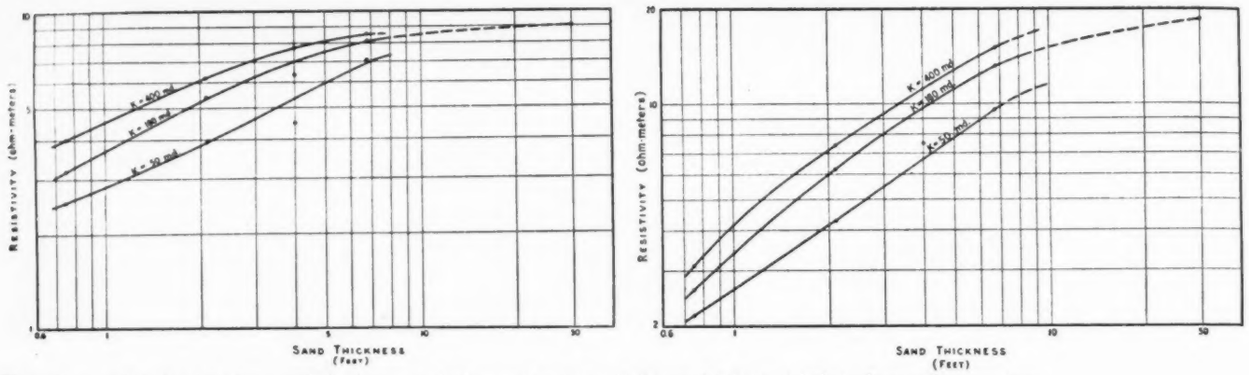

Figs. 9 and 10. Resistivity-sand thickness relation using 5-in. (left) and 20-in. (right) electrode spacing

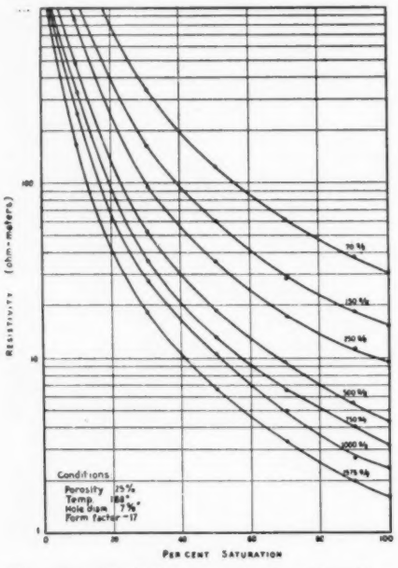

Fig. 11. Resistivity-percent saturation

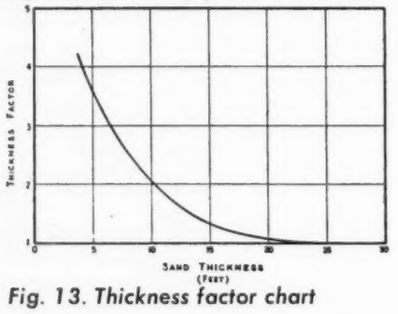

Fig. 13. Thickness factor chart

consider the influence of permeability and sand thickness. The weighted interstitial saturation was determined by taking the sum of the products of sand thickness × permeability × saturation and dividing by the sum of the products of thickness × permeability. A similar calculation was made for the resistivity saturation, S_2.

Conclusion

The results of the tests present a relative term depth of penetration for comparing the respective amounts of the formation measured for changes in electrode spacing. By means of this term it becomes possible to construct a resistivity-penetration curve that can be divided into two regions of analysis. First, that portion of the resistivity curve affected by the presence of drilling fluid, and second, that value of resistivity measured beyond the influence of the drilling fluid. Correlation for infiltrated portion of the sand represents resistivity as a function of permeability at a constant sand thickness. The cross plot of these data illustrate the very large effect sand thickness has on the measured resistivity. Therefore, it is possible for a thick sand of low permeability to record a higher resistivity than a thin sand of high permeability.

In the analysis of the second portion of the resistivity curve calculations are made for the percent water saturation by choosing values of resistivity measured beyond the effect of mud infiltration. To do this it was necessary to construct a curve relating sand resistivity to the percent saturation. For the thinner sands a thickness factor curve aided in correcting the measured resistivity for sand thickness. Calculations were made on 8 sands cored in the well which differ in thickness and permeability.

After weighting the saturations for thickness and permeability it was seen that the calculated saturation is greater than the critical saturation. This would suggest that these sands would initially produce some water.

Acknowledgment

The author wishes to express his sincere appreciation to Howard C. Pyle in directing the work, and to John E. Sherborne and Stewart Hagestad of the Union Oil Company of California and John C. Stick, Jr., of the Lane-Wells Company for their generous help in performing the tests, and to the Union Oil Company of California for its release of the data presented.

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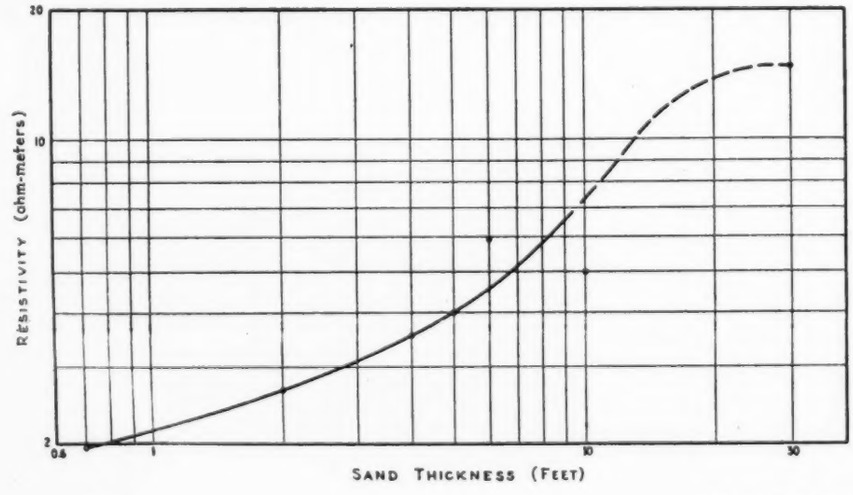

Fig. 12. Resistivity-sand thickness relations. Sand permeability, 180 md. Electrode spacing, 63 in.

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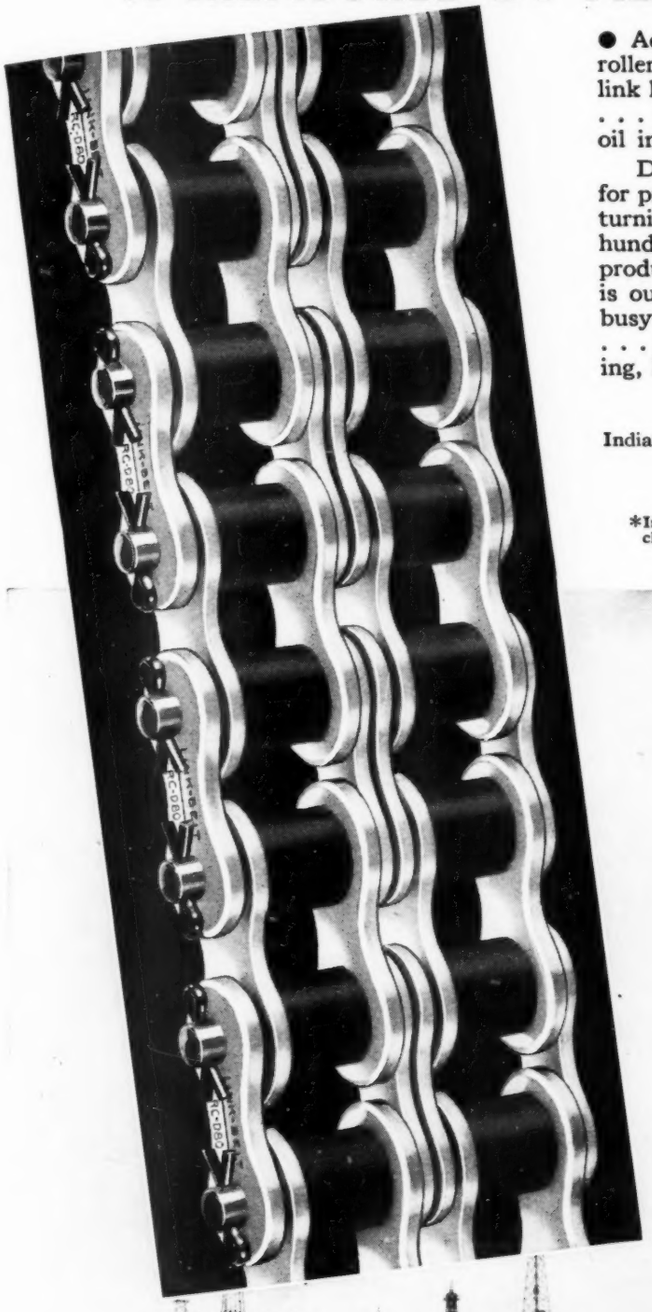

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Some Factors Influencing the Declining Rate of Crude Oil Discoveries*

The Geologist's Responsibilities in the Present Situation

By L. F. McCOLLUM[1]

Abstract

THE feeling that the exploration for new reserves should be accelerated is shared generally by most well-informed oil men today. The subject of the decline in crude oil discoveries is of particular importance to the geologist, who represents the backbone of the finding branch of the American petroleum industry. Upon his shoulders rests a major portion of the responsibility of maintaining ample crude oil reserves with which to supply the necessary war requirements and essential civilian needs. The importance of the independent producer and the oil promoter in the finding effort of the industry cannot be over-emphasized and everything possible should be done to encourage their continued operation and success.

Viewed over a substantial period of time, it would appear that the declining discovery rate has been influenced more by other factors than by material shortage, manpower shortage, and crude price. In the immediate present, however, it is obvious that each of these factors is seriously influencing the rate of discovery. The removal of these factors as retarding influences is perhaps the problem of others than the geologist, and it is hoped that to the extent necessary they will be corrected.

The relationship between the discovery rate in the Mid-Continent-Rocky Mountain-Gulf Coast region and the effect of the opening of new geological or prospective provinces within this area demonstrates the importance that new prospecting territories have played in maintaining the discovery rate. A study of the relationship between discovery rate and exploration methods indicates the importance that each new finding tool has played in maintaining finding rates. The influence of these two factors on the discovery rate within the area under discussion over the last three to seven years has been profound and doubtless has been of major consequence in the declining rate of discovery in the entire United States.

Geologists and geophysicists should recognize their responsibility of extending the search for oil into new provinces that heretofore have received little, if any, attention. They should also accept the responsibility of providing new finding tools and of improving present exploratory methods.

To be invited to address a meeting of the American Association of Petroleum Geologists is an honor that any person will cherish for a long time. I am conscious of the weight of responsibility placed upon a speaker before such a group of oil-finding scientists. I want to thank you for honoring me with an invitation to address you today on the subject of *"Some Factors Influencing the Declining Rate of Crude Oil Discoveries—The Geologist's Responsibilities in the Present Situation."*

Decline in Discoveries

The decline in crude oil discoveries has been the topic of discussion by the producing branch of the oil industry for the last several months. The general decline in discoveries that has obtained from 1935 through 1942, is viewed as a hazard to this nation's supply of crude oil and products. This subject is of prime importance to the geologists who represent the finding branch of the American petroleum industry. Upon our shoulders rests the responsibility of keeping the American nation supplied with ample crude oil reserves to meet the necessary war requirements and essential civilian needs.

Recent estimates released by the P.A.W. of crude oil production required to meet the war needs and to supply essential civilian uses for the year 1943 are slightly less than 4,000,000 bbl. daily, with a peak production of perhaps 4,200,000 to 4,600,000 bbl. daily during the last quarter of 1943. With the anticipated production decline in the older producing areas, the present shut-in capacity to produce in some of the newer areas will be taxed to meet the required production without physical waste.

I believe the feeling is shared generally by those informed on the oil industry that exploration for new reserves should be accelerated. The volume of oil discovered has declined over the last several years, whereas production has continued to increase. Without debating the question of whether or not discoveries should be increased, let's examine the record and attempt to determine why discoveries are declining, and endeavor to find a solution to reverse this trend. The discussion in this paper is based on data obtained largely from the Mid-Continent-Rocky Mountain-Gulf Coast region. The conclusions reached are probably generally applicable throughout the entire United States, inasmuch as the Mid-Continent-Rocky Mountain-Gulf Coast region produces approximately 80 percent of the nation's crude oil.

In the upper left-hand corner of Fig. I is shown the volume of discoveries of crude oil reserves, by years

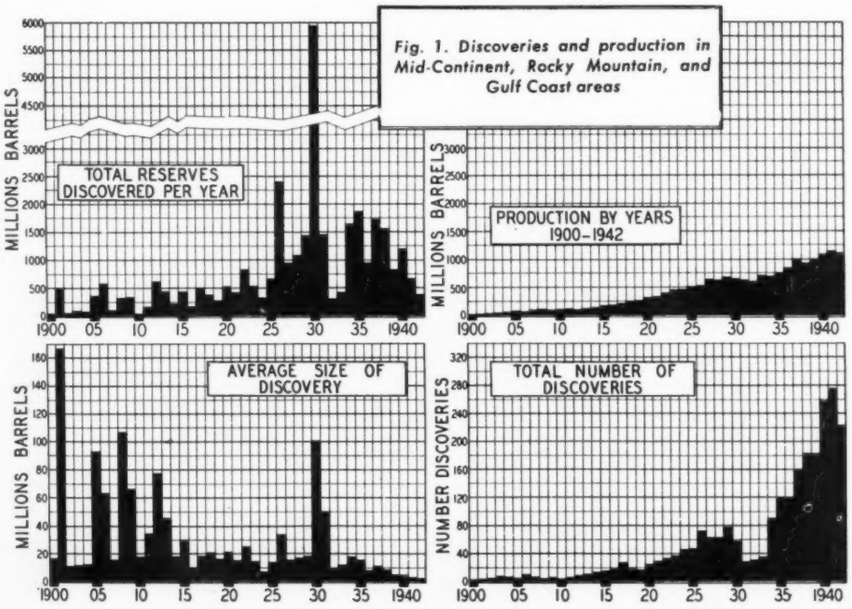

Fig. 1. Discoveries and production in Mid-Continent, Rocky Mountain, and Gulf Coast areas

*Presented before American Association of Petroleum Geologists, Fort Worth, Texas, April 7-9, 1943.

[1]At the time this paper was written McCollum was president of the Carter Oil Company. He has since been promoted to the Standard Oil Company of New Jersey, New York, New York.

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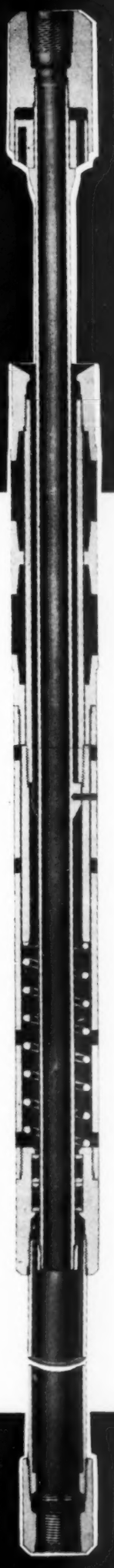

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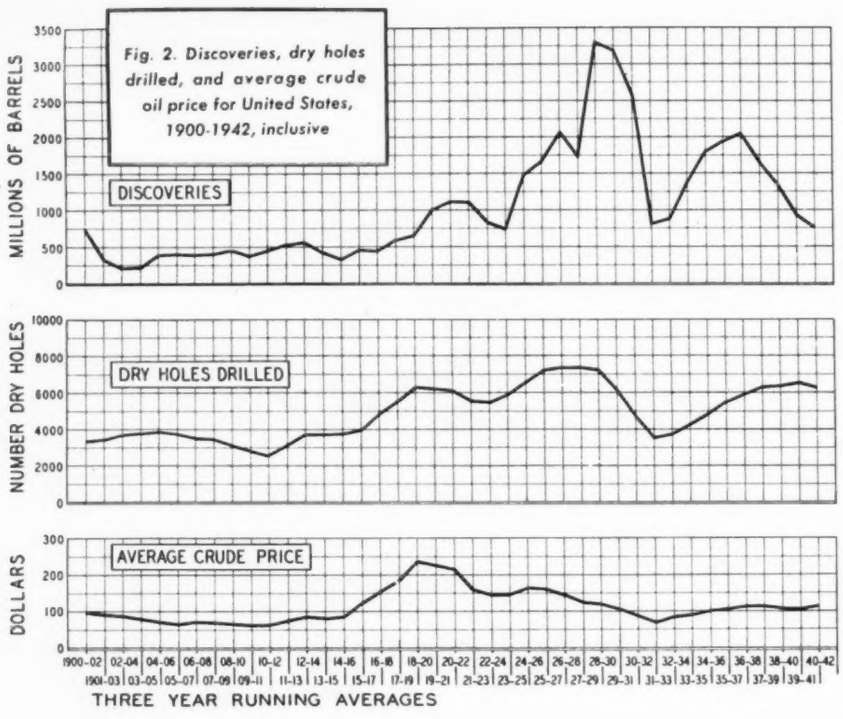


Fig. 2. Discoveries, dry holes drilled, and average crude oil price for United States, 1900-1942, inclusive

(1900-1942, inclusive), in the Mid Continent-Rocky Mountain-Gul Coast region of the United States, which comprises P. A. W. Production Districts 2, 3, and 4. Revisions in estimates of discoveries have been credited or charged as the case may be to the year in which the discovery was made. This chart is not new, but is presented to support the statement made earlier that discoveries have declined over the last several years. Discoveries were approximately the same in 1942 (375,000,000 bbl.) as in 1931-33, the "depression" years. This figure compares to discoveries of 655,000,000 bbl. in 1941 and 1,185,000,000 bbl. in 1940. The discovery of approximately 6,000,000,000 bbl. of oil in 1930, the year of the discovery of the East Texas field, stands out strikingly and needs no comment. It is the decline in later years that interests us most at the moment, and to which we will devote most of our discussion.

In the upper right-hand corner of Fig. I, production is plotted by years from 1900 to 1942, showing a rather constant increase in production to a peak in 1941 of 1,139,000,000 bbl. The trend in production during recent years is inverse to that of discoveries, giving rise to the concern that is felt today by the industry that we may fail to meet without wasteful production practices our future demand for crude oil. In the lower left-hand corner of Fig. I you will see the average size of discoveries by years from 1900 to 1942. The peaks in the years 1901, 1905-06, 1908-09, 1912, and 1930 stand out strikingly, as do also the scarcity of peaks in later years and the decline in average size of discoveries since 1930.

In contrast to the volumetric decline in discoveries during the last three to seven years, and the decline in the average size of discoveries for the last ten or twelve years, is the total number of discoveries shown in the graph in the lower right-hand corner of Fig. 1. With the exception of the years 1931-33, there has been a gradual increase in the number of discoveries from 1900 to 1942, with the peak number of 275 discoveries being attained in 1941. Despite this increase in the number of discoveries, graphs to the left on Fig. 1 indicate that the total volume of oil discovered annually has declined. This raises the doubt that our prospecting territory still holds hidden fields of large magnitude compared to such fields as East Texas, Oklahoma City, Yates, Conroe, Salem, Hobbs, etc.

The decline in total completions for this area from 23,148 wells in 1941 to 12,929 wells in 1942 (44 percent) is striking. This decline is probably the direct result of federal spacing regulations and the shortage of materials—the shortage of materials creating the necessity for federal spacing regulations. The decline in dry holes drilled from 6345 in 1941 to 4967 in 1942, and the decline in wildcat completions of from 3255 in 1941 to 2956 in 1942, may also be attributed at least partially to the shortage of materials.

It is obvious, at least during 1942, that the shortage of materials influenced crude oil discoveries. With a continuing shortage of necessary materials and equipment, the rate of discovery may decline further. The search for new prospects and also the drilling of additional wildcat wells will be influenced by the material situation. This problem is one that the industry must solve, and is receiving a great deal of attention. As the matter is in capable hands, it is hoped that sufficient materials and equipment will be available during 1943 for the drilling of the necessary number of wildcats and to permit other exploratory work.

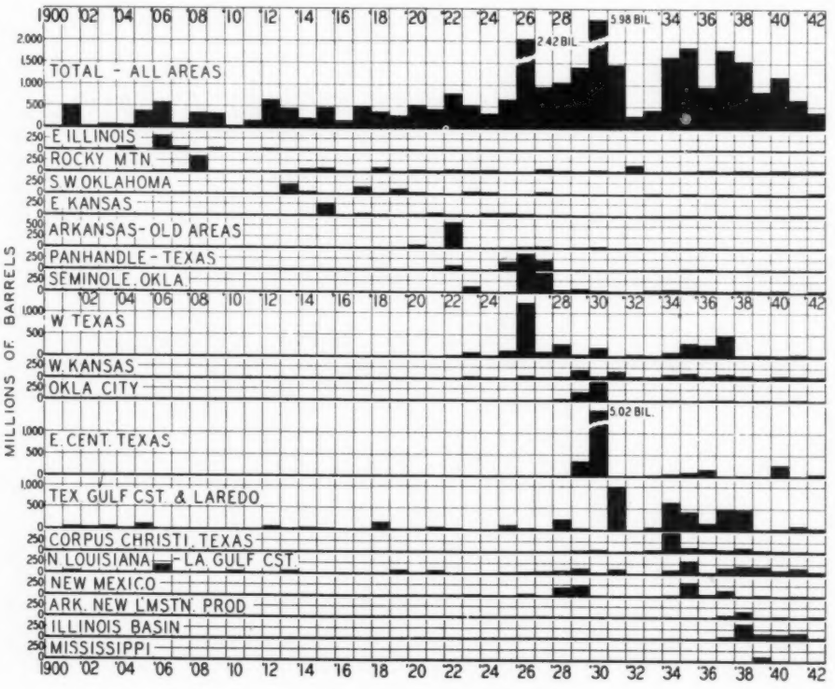


Fig. 3. Discoveries in Mid-Continent, Rocky Mountain, and Gulf Coast

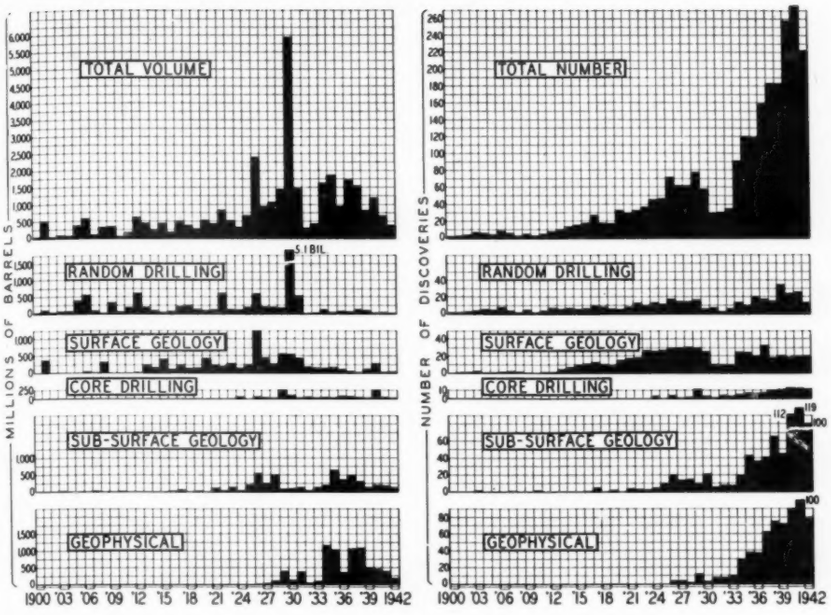


Fig. 4. Methods of discovery in Mid-Continent, Rocky Mountain, and Gulf Coast areas

Manpower Shortage

The shortage of manpower in the search for new discoveries is becoming acute. A number of manpower surveys are in the process of being compiled. The Lovejoy committee on manpower, in a preliminary report to the P.I.W.C., states that the average loss of personnel by the petroleum industry to the armed forces runs approximately 15 percent, with the experience of individual companies varying from 5 to 35 percent. This committee says that "the chief complaint running through the replies (to their questionnaires) shows a great difficulty in maintaining adequate technical men. This seems to be general, and is spread through all branches of the industry."

The technical staffs, the leasing staffs, and other members of the finding staffs of the operators, both small and large, have been severely depleted. Geologists and geophysicists, as well as others connected with the finding branch of the producing industry, have answered the call to the colors unhesitatingly. Of the total membership of the A.A.P.G., 14 percent are either in the armed forces or in government-civilian service and hence are not available for exploratory work during 1943. Final figures on the loss of geophysical personnel have not been completed by the S.E.G. Preliminary figures indicate that 30 percent of the geophysical personnel employed at the time of the Pearl Harbor attack have now gone into the services. Drilling crews for wildcat drilling purposes are increasingly harder to obtain and an acute shortage in drilling personnel threatens. Other members of the finding branch of the producing industry are occupied in work either directly or indirectly connected with the war, and hence are not fully available for exploratory work. There has also been a severe loss of other personnel engaged in the general effort of discovering new reserves.

Perhaps in the immediate present the importance of the manpower problem overshadows that of the material problem. In order to find the oil that may be necessary in the future, there should be an immediate acceleration in the amount of geological and geophysical effort and the men required for this acceleration should be made available.

Influence of Price

No discussion of the principal factors influencing discovery rates would be complete without examining the effect or influence of price. Fig. 2 shows by three-year running averages the relationship between average crude oil price, dry holes drilled, and discoveries from the entire United States for the period 1900 to 1942. This chart shows a generally direct relationship between the average crude price, dry holes drilled (a measure of finding effort), and discoveries, but in recent years, with which we are principally concerned, this direct relationship fails to maintain itself.

The search for new reserves as measured by the dry holes drilled, has been generally upward from 1933 through 1941, with a decline in dry holes completed of 7128 in 1941 to 5500 (23 percent) in 1942. From the year 1934 through 1942, the price of crude oil has remained fairly constant, fluctuating from a low of $0.96 per bbl. in 1935 to $1.17 per bbl. during 1942. Contrasted, however, to the somewhat uniform crude price from 1934 through 1942, and contrasted to the increased number of dry holes drilled as a measure of exploratory effort during the same period, is the general decline in reserves from 1937 through 1942. Dry holes drilled increased every year from 1933 through 1941, except for a slight decrease in the year 1938. Discoveries, however, declined from approximately 2,075,000,000 bbl. in 1937 to 420,000,000 bbl. in 1942, with declines each year except in 1940.

This lack of correlation between discoveries, the number of dry holes drilled, and the price of crude oil during the last few years requires further examination. The direct relationships between price, search, and discoveries prior to this period, leads to the possible conclusion that other factors are operative today that were not present prior to this time. It would appear from this chart that the major factor influencing this decline in discovery rate is neither the material shortage, the manpower shortage, nor the price of crude oil. It is probably worthwhile, then, to look further in search of other factors that are influencing the declining discovery rate for the last several years.

Other Factors

Fig. 1 indicates that the total number of discoveries by years from 1900-1942, and particularly during the last few years, with the exception of the year 1942, have increased tremendously, as a matter of fact increasing from approximately 30 discoveries in number in 1931 to 275 discoveries in 1941. During approximately the same period, with the exception of a few minor fluctuations, the average size of discoveries has declined from 18,000,000 bbl. in 1934 to less than 2,000,000 bbl. in 1942.

Upon examining the relationship between the discovery rate in the entire Mid-Continent-Rocky Mountain-Gulf Coast region, and the effect of the opening of new geological or prospective provinces within this area, one is impressed with the importance that new prospecting territories have played in maintaining the discovery rate. A similar examination of the relationship between discovery rate and the exploration methods responsible for finding oil pools in this region indicates the importance that new finding tools have played in maintaining finding rates. A thorough study of the influence of these two factors on discovery rates during the last 40 years and a critical examination of the declining discovery rate during the last three to seven years, indicate that "the old field from which we have been raising our new crop of oil pools is becoming increas-

ingly unproductive as a result of being constantly recultivated," and that the implements that we have used to find oil in these fields "are becoming increasingly dull and ineffective." Despite the improvement in the technique of finding oil over the last several years, the tools that we have used, although capable of finding an increasing number of fields, are less effective from the standpoint of the amount of oil found.

Fig. 3 shows the relationship between the discovery rate in the Mid-Continent-Rocky Mountain-Gulf Coast region and the opening of new geological producing areas within this region. As a new area is proved, exploration effort increases and the finding success rapidly builds up to a peak. Discoveries later run their course, after the new areas have been combed, and the discovery rate then descends. Fig. 3 at the top shows discoveries in the Mid-Continent-Rocky Mountain-Gulf Coast region by years from 1900 to 1942. Beneath this is shown discoveries by years in certain geological producing areas for the same period. Note the direct relationship or influence between peak years of discoveries by geological provinces and the discoveries for the region as a whole. Note the influence of Arkansas discoveries in 1922 on the total discoveries for the area under discussion. Also, note the influence of discoveries in the Panhandle of Texas, the Seminole area of Oklahoma, and the West Texas area in the years 1925, 1926, and 1927 on total discoveries for the Mid-Continent-Rocky Mountain-Gulf Coast region. Generally, it may be seen from Fig. 3 that without the opening of new prospecting territory, discovery rates could not have been maintained. As the area of active search in the Mid-Continent-Rocky Mountain-Gulf Coast region has not been expanded materially in recent years, the decline in the rate of discovery may be due to the exhaustion of our hunting grounds. In other words, "our finding field is becoming sterile from being constantly ploughed over."

The relationship between the volume of reserves discovered and the exploration method responsible for the discovery of oil pools in the Mid-Continent-Rocky Mountain-Gulf Coast region for the years 1900-1942, inclusive, is illustrated on Fig. 4. This chart also shows the number of discoveries by exploration methods. On the right-hand side of this chart at the top is the same graph shown in the lower right-hand corner of Fig. 1, which brings out the increase in the number of discoveries over the last 40 years. Also, on the right-hand side of this chart, is shown the total number of discoveries by each exploration method for the same period. Generally, this shows that each method of exploration is still effective insofar as its ability to find prospects is concerned. On the left-hand side of Fig. 4 is shown the amount of oil discovered annually from 1900 to 1942, inclusive. At the top of the chart there is again shown volume of discoveries, by years, for the period under discussion.

Beneath the graph at the top in the left-hand corner of Fig. 4 is shown the total oil discovered by years by the various finding methods. It is clear that there has been a rapid increase in the amount of oil discovered soon after the inception of each new method and that each method now is in a period of lessened effectiveness. It is also obvious that, without the introduction of new finding methods, total discoveries would have been much smaller.

Figs. 3 and 4 clearly illustrate that our finding tools are less effective today than at any time heretofore from the standpoint of the volume of oil being found, and further illustrate the extreme need for developing new prospective territory in the Mid-Continent-Rocky Mountain-Gulf Coast region if the discovery rate is to be maintained. These two factors have profoundly influenced the discovery rate over the last three to seven years, and, in my judgment, have been major causes of its decline.

Geologists and geophysicists should recognize the responsibility that they bear. We are the ones most capable of either improving our known exploration methods or of discovering new discovery methods. It has been obvious to most of us for some time that the relative effectiveness of our exploration tools is decreasing. Recognizing this fact, we should exert our influence on those who look to us to find oil to provide us with ample materials, manpower, and money to sharpen our present tools and to devise new ones. Likewise, it is up to us to extend our search for oil to new provinces. We know that we cannot fertilize our old finding field and grow a new croy of oil pools. We must move into new territory. This will require carrying on exploratory activities in regions that heretofore have not received a great deal of our attention. It will be necessary to search for oil and drill wells in regions remote from our place of former activity, or from our operating headquarters. Our search should be more audacious and less cautious. Assuming that the same average size of discoveries during the last three years obtains for the next five years in the region being discussed, it will then be necessary to drill 5100 wildcat wells annually, or 1.75 times the number of wildcats completed in 1942, to discover the oil we will produce annually.

The importance of the independent producer and the oil promoter in the finding effort of the industry cannot be over-emphasized. There are many individual operators who do a large share of the wildcat drilling, and who often employ more geology in their operations than they themselves realize. The industry owes much of its success to these operators and everything possible should be done to encourage their continued operation and success.

We must accept the responsibility for improving our discovery rate. The improvement of exploratory methods and the discovery of new methods may bring increased costs. Likewise, exploring for oil in new regions, some of which do not appear attractive, may result in increased costs. These facts should be honestly and courageously faced. If we are to succeed in our efforts to maintain our discovery rate, the necessary funds to carry on the needed search must be provided.

The finding branch of the producing industry may be required to initiate and carry out an aggressive research program, designed to discover new finding tools or to improve our present methods. Such investigations might go further into the possibility of new instruments based on chemical, physical, or electrical phenomena. Enlarged regional stratigraphy and structural studies are desirable. Coöperative effort in this regard should yield valuable results.

As geologists, we may contend that the declining discovery rate is due to the material shortage, the manpower shortage, or to inadequate crude oil prices. If we face the facts, however, I believe we must admit that more potent factors in causing this decline are our failure for nearly a decade now to develop any radically new or improved finding techniques and our insistence on ploughing the same old fields. We need better implements and new fields to use them in.

The oil geologist's future is perhaps brighter today than ever before. Because of the need for exploration personnel, there will be a demand for his talents. The reward for qualified "explorationists" will be great. We are happiest when we have a job to do and are busy doing it. Upon our shoulders rests the responsibility for increasing our discovery rates. We may approach this task with confidence that the job can be done, and we will do it.

Acknowledgment

I wish to express my appreciation to members of The Carter Oil Company staff for their assistance in assembling the statistical data and in preparing the charts; also, to these people and other associates for their helpful suggestions and constructive comments.

P 390.1
P 971.

Petroleum Exploration and Development in Wartime*

By

E. DeGOLYER

Assistant Deputy Petroleum Administrator

THE coming of war has wrought sharp and sudden changes in the pattern of the oil industry. The most obvious and most striking of such changes have been in the fields of transportation and refining.

A third of the world's total oil production formerly started to market, tanker-borne, over the waters of the Gulf and Caribbean. Most of this oil went to our North Atlantic ports, supply points for the world's greatest consuming center. This tremendous traffic, disrupted by the loss of tankers as a result of requisition for military purposes and as a result of destruction by the activity of enemy submarines, has had to be substituted largely by such lines of supply as could be improvised without loss of too much time. There was no single solution for this gigantic problem nor is it likely to be entirely solved for some time to come. It has been solved in part, however, by re-arrangement, reversals, and patching up of existing pipe-line systems; by overland transport of crude and products in tank cars on a scale never before attempted; by barging over inland waterways; and through the construction at long last of the "big-inch" line, the first leg of which is just being put into operation as far as Norris City, Illinois. The tank car traffic alone, reaching a peak of deliveries of 856,710 bbl. per day into District 1 during the week ending September 19, 1942, and accomplished at an expense of millions of dollars in extraordinary transportation costs, defrayed by Defense Supply Corporation, and by the mobilization of tank cars from all over the Nation, is a story worth the telling but by some of those who directed it and at the cost of more time than is available at the present.

Rapidly mounting needs for the fighting grades of gasoline — the 100-octane and 91-octane gasolines — for toluene, for the butadiene constituent of synthetic rubber, for greatly improved aviation and Diesel lubricants, and for numerous specialty products—chemicals to cutting oils—have revolutionized the refining industry and embarked us upon a construction program running into hundreds of millions of dollars and intended to supplement our already great refining industry. Products which only a few years ago were almost laboratory curiosities today must be produced in volume. The industry has changed from one in which ordinary motor fuels were the products in prime demand to one in which motor fuels are of secondary importance and the high-octane products and fuel oils are of first importance. The industry bids fair to develop into one of the most important of the chemical industries. As Joseph Stalin was recently quoted by the head of the British Oil Mission to the United States, "This is a war of engines and octanes."

The problems of the producing branch of the industry—those of exploring for new fields and exploiting existing fields — have been relatively unimportant up to the present time. Actually, the only operating problem that has been of serious concern has been that of rationing our sorely shrunken and continuously shrinking stock of oil-well supplies.

Problem of Production

Indeed, in the early days of our preparation for war, we hardly recognized the existence of a problem of production. The nation was assured by various leaders of industry that the industry could meet any probable requirements that war was likely to thrust upon it. "By the mere opening of valves we could overnight add 30 percent to our production" is a fair example of the more restrained and considered type of statement to which I refer and it continued with the implication that this would take care of any extraordinary requirements due to war in addition to providing for ordinary public needs for a period of two years. There can be no question but what these statements were made honestly and in good faith. On behalf of those who made them it might even be said that there were certain assumptions implicit in the statements. The leaders of the industry could remember the last war. Drilling equipment—notably casing—became scare at times and was hard to get but drilling was never restricted. There was no price control nor was there any critical shortage of manpower. Military operations, with but few unimportant exceptions, required the products that the industry was accustomed to manufacture. Rationing in civilian consumption was so little of a problem that it was solved voluntarily by the seven gasoline-less Sundays and a few heatless days.

It is true that as we went into the present crisis, the industry was not reliably informed with regard to its ability to produce and that it had overrated somewhat its productive capacity. At the end of ten years of producing under proration, estimated potentials had been built up in some areas to fantastic and unreal figures. California and Kansas are fair examples of such practice.

The industry, therefore, did not understand the magnitude of the demands that it was to face nor the severity of the restrictions under which it would have to operate and it also overrated its capacity to produce. The net result of its overly optimistic statements made 18 months to two years ago when the inevitability of our entrance into the war became increasingly apparent, was to carry an unwarranted conviction to administrators who do not have to follow the varying fortunes of the oil industry. Some such administrators to this very day are prone to deny to the industry supplies and assistance that are essential in the mistaken belief that the "crack the valve" idea is correct. This mistaken conviction has led even to suggestions that the industry might enjoy a holiday from drilling operations in order to make the critical materials such as steel used in such operations, available for other urgent needs.

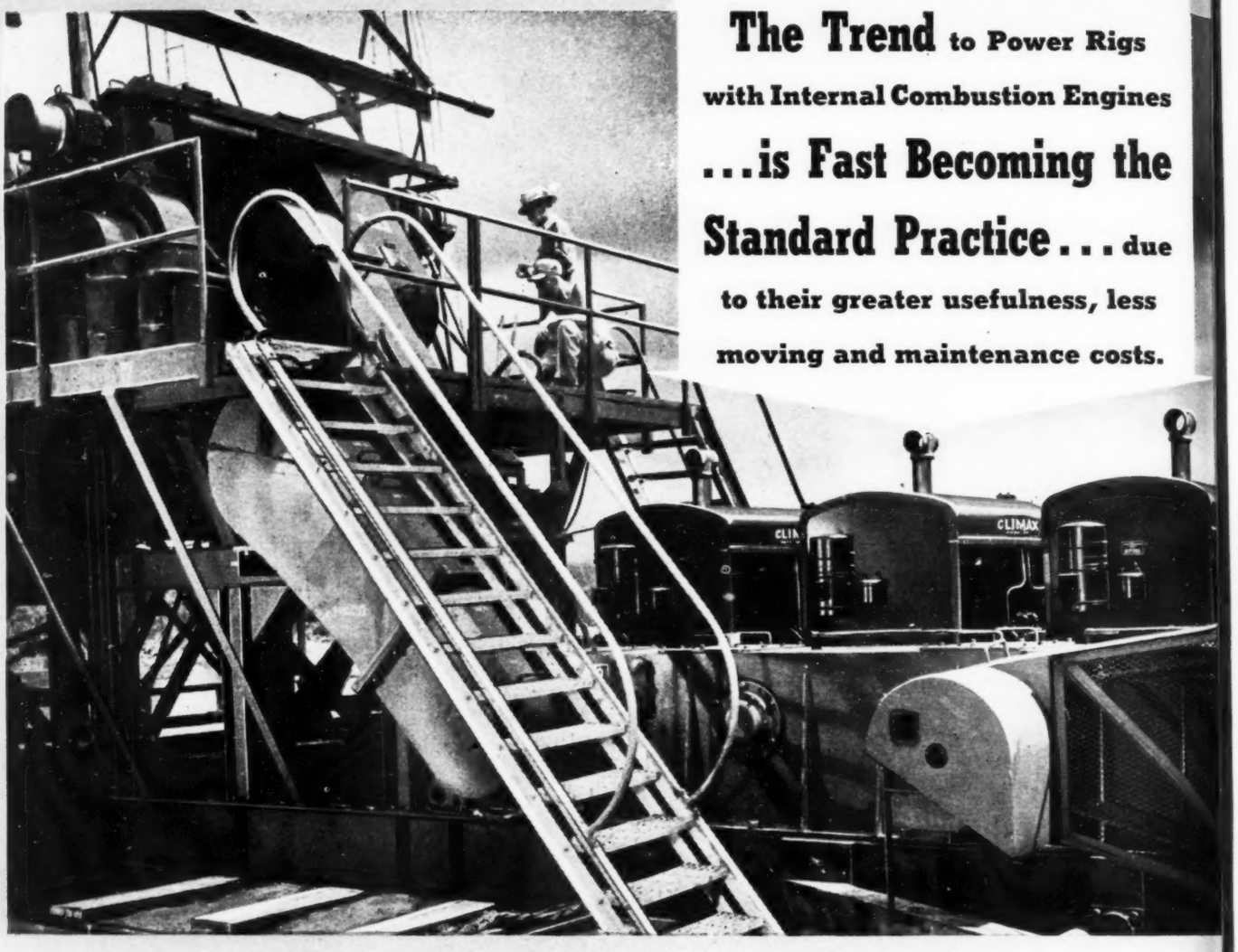
TABLE I

Results of exploratory drilling

Year	Total wildcat wells drilled	Successful wildcats	Number new fields discovered	Total new reserves discovered*, million bbl.	Discovered per field, million bbl.
1934	.....	.....	86	1699	19.7
1935	.....	.....	104	1934	18.6
1936	.....	.....	104	1894	18.2
1937	2224	222	148	2119	14.3
1938	2638	294	166	1894	11.4
1939	2589	224	170	943	5.6
1940	3038	302	217	945	4.3
1941	3264	503	209	361	1.7
1942	3045	493	261	317	1.2

*Revisions, extensions, and new horizons are credited back to year of field discovery.

*Presented before American Institute of Mining and Metallurgical Engineers, Annual Meeting, New York, New York, February 14-18, 1943.



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POWER TAKE-OFF AND SUPPORT—Insures rigid transmission mounting and maintains shaft alignment.

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Although the changes in the producing branch of the industry, up to the present, have been those of restriction rather than expansion and have been somewhat less spectacular than those of refining and transportation, production does have problems that are real and of continuing and increasing importance.

We are not finding oil fast enough and we have not found oil fast enough for the last four years to replace that which we have produced and consumed and so to maintain our reserves on balance. Now war changes our standards and our values. We are not concerned with this falling off in the rate of discovery for its effect on our reserve position. We are moved by the stern need to increase our daily productive capacity and the discovery of new pools is the quickest and most effective method of achieving such result at a minimum expense of manpower and of scarce and critical materials.

Analyses of the poor results that have attended our exploratory efforts over the last four years, probable causes, and urgent requests to increase the exploratory effort have been directed repeatedly to the oil industry by the Office of Petroleum Coördinator and by its successor, Petroleum Administration for War, during the 18 months of their existence. These warnings and exhortations have been received by the industry with an understandable passiveness. During the entire period we have had and still have an excess capacity to produce. Why, one might argue, be concerned with the development of still greater capacity to produce while we still have a productive capacity of three to four hundred thousand barrels per day than can find no outlet. The answer is that part of this excess productive capacity, which is largely in the Permian Basin of West Texas and New Mexico, in the Gulf Coast of Texas, and in Southwest Texas, is not presently accessible because of transportation restrictions and that we have not yet had to meet our full war demand. The transportation problems will have to be solved in order that we can avail ourselves of our full productive capacity but even then, if estimates are at all correct, we will need more oil than we are able to produce. In certain areas we will face shortages in productive capacity within the very near future.

As our standards of value for reserves have changed to terms of immediately producible capacity instead of ultimately producible barrels of oil so have our standards of value for conservation. When we urge upon the industry the necessity for conservation in the production of known deposits we are considering the problem in terms of good production practice. We are not so concerned with a desire to conserve oil and gas to be produced 20 or 30 years into the future, although, other things being equal, this phase of the problem is not to be neglected. We are moved by the stern need to keep our daily productive capacity at the highest possible rate for the next two, three, and four years. The war need is paramount and it requires, we hope, the relatively short view.

Status of Exploration

Let us look at the basic problem — that of exploration. What is its status? In terms of effort, as measured by the number of wildcat wells drilled and by the number of geophysical and core drill crews in operation, and these are perfectly satisfactory indices, it is at an all-time peak. More than 3000 wildcat wells have been drilled annually for each of the last three years; a number greater than that during any other time for which records are available. In excess of 300 geophysical and core drill crews were employed throughout the last year and are being employed at present—another record-breaking performance exceeding by more than 12 percent such prospecting activity for any previous year. We can only conclude that our exploratory effort is at an all-time high.

The results of this effort, however, are below our hopes and below our necessities. The results of exploratory drilling 1934-1942 are set forth in Table 1. The most notable facts developed by this table are (a) the sharp falling off in reserves discovered annually since 1938, (b) the increase annually in number of fields discovered and, (c) the decreasing average reserves discovered per field.

Our real problem is probably that of the tremendous rate of consumption of crude oil and products at which we have arrived. There is nothing in the past history of our efforts at exploration for new fields to justify the belief that we can continue to discover indefinitely the almost one and a half billion barrels that we consume annually. If we review critically our past record of discovery we find that, except for the 1926-1938 period which I propose to call the geophysical period and which I will discuss separately in greater detail, there were only two years in the whole history of the oil industry when we discovered as much as one billion barrels of reserves in a single year. One of these years was 1901, the year of Spindletop and other important fields of the Gulf Coast of Texas and Louisiana. The other year was 1921, the year of discovery of the great Long Beach, California, field.

During the geophysical period, the period of 1926-1938, except for the years 1932 and 1933, which were years of the depth of the depression, with regard to the oil industry as well as the national economy, we discovered well over a billion barrels annually. Even including these two bad years, thanks to the discovery of Oklahoma City, Kettleman Hills, and East Texas, neither of which were geophysical discoveries, during this period we discovered an average in excess of two billion barrels annually. A critical consideration of this period suggests that prospecting was marked by our use of a new and highly effective prospecting tool-geophysics — and that during that period we discovered reserves that, lacking such prospecting device, or one equally useful, it might have taken us 30 to 40 years or even longer to discover. Furthermore, additional consideration of the history of oil prospecting and particularly the continuous decrease in average size of fields discovered, suggests that we may be approaching the end of an era — that of prospecting for oil in structural traps—as well as the end of a period—that of the search for such traps by geophysical methods.

The nation, however, is interested in results rather than techniques. Again taking the short view imposed by war, what we require at present is increased productive capacity and our best chance of getting it is through the discovery of new fields. If they cannot be found at our present rate of exploration, efforts must be increased. The Petroleum Administration for War has recommended the drilling of 4500 wildcat wells during the present year as compared with the 3045 wildcat wells drilled last year. The individual companies are being approached and asked to discuss their prospects and their proposed exploratory programs and every effort will be made to step up our rate of oil-finding. The war has placed only one requirement on those engaged in petroleum exploration and development — to find more and more oil—of the right type and in available places — with less and less equipment. This statement is simple; it is the problem that is complex. Yet the problem must be solved.

Lest I leave you with the feeling that I am a pessimist, may I say that I believe that there are yet unknown fields of great magnitude still to be discovered within the United States. I refer to search for fields of the stratigraphic trap type to which the mammoth East Texas field and the great Coalinga Deep fields belong. This, however, is Mr. Levorsen's thesis and I will not attempt to develop it. It is enough for my present purpose to say that at present we

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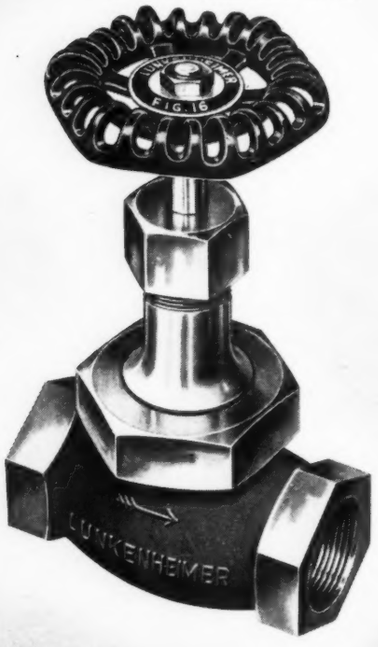

Replace trimmings in body and regrind.
Extension on bottom of hub should enter neck of body while regrinding.
Allow union ring to remain loose
4th OPERATION

When finished regrinding remove trimmings from body.
Remove pin.
Thoroughly cleanse seat and disc seating surfaces of abrasive.
5th OPERATION

LUNKENHEIMER VALVES

have no easy method of discovering such fields.

The business of exploitation of known deposits is not so difficult nor in such a bad way at present as is that of exploration but it also has its problems. The need for enormous quantities of steel to implement the war have made necessary drastic reductions in the normal rate of consumption of steel in oil field development. This necessity gave rise to Conservation Order M-68, which was issued on December 23, 1941, and which was intended to reduce the consumption of oil-field supplies to 60 percent of that used in 1941 and to ration such reduced supplies to the industry. This order placed no restrictions on the all-important matters of geological and geophysical exploration nor on the drilling of wildcat wells. It granted automatically the drilling of one oil well properly located on each 40 acres and likewise one gas well to each 640 acres. There were other automatic standards for the use of oil-field equipment and, since it was realized that no set of general standards would suitably meet all cases, provision was made for the granting of exceptions.

This order has performed its principal function admirably. During the year 1941, 29,574 wells were drilled not including salt water disposal and input wells. During the year 1942, similarly 17,872 wells were drilled. The order was intended to restrict drilling in 1942 to 60 percent of the drilling in 1941. In performance it actually restricted drilling in 1942 to 60.4 percent of drilling in 1941.

Order M-68 was amended from time to time to meet special cases. Our proposed drilling program for the present year is for 16,000 wells of which it is hoped chat 4500 wells will be wildcat wells. Obviously, as less and less material is available for drilling and as our needs for production mount, the operation of any restriction will have to be less automatic and more discretionary authority will have to be used.

A shortage of manpower in the producing branch of the industry threatens to become as important during the present year as is the material shortage. This condition, as well as the necessity for maintaining productive capacity, makes highly desirable the unitization of those fields where it would be most effective as well as to promote pressure maintenance, repressuring and secondary recovery programs and such unitization, the Petroleum Administration for War is prepared to promote to the full extent of its powers.

☆☆☆

P 422.143.
P 732.1
P 094.1

Maintenance of A.P.I. Oil Field Equipment Standards*

By
H. W. LADD
Stanolind Oil and Gas Company

AMERICAN Petroleum Institute equipment standards must be appraised under existing conditions with the purpose in view of determining their value to the war effort. We already know that they are economically applicable to oil-field production practices.

We all want to help win the war. If this could be done by discarding specifications entirely, none would hesitate. It is a fact, however, that A.P.I. specifications are already assisting the war effort, both directly and indirectly. Therefore, let us consider that which has been done and whether anything further is required to better accomplish this purpose.

Specifications cannot be changed without far-reaching effect, and none should be made without careful evaluation of the ultimate result, particularly when the change affects the high standard of quality previously maintained. It is recognized that many materials have been downgraded because of the unavailability or critical nature of their composition. We must meet this situation as it comes whether we like it or not, and must decide whether the standard of our specifications shall be lowered to meet the temporary situation, or their high quality maintained and the material used outside the standards. The possibility of further simplification is always present. Conservation of materials through proper application of specifications must receive full consideration.

A brief review of events leading up to the present status of A.P.I. specifications may be properly prefaced by the statement that few industries have found the need for equipment standards so vital as has petroleum production. As time went by and operations spread over our own country and throughout the entire world, a multitude of different specifications were developed to meet the variable or different conditions encountered, each representing a local or individual idea. This led to an impossible situation, wherein production and use of many unnecessary items involved waste of both material and labor.

For the last 25 years many qualified representatives of manufacturing concerns and petroleum operators have actively contributed their efforts toward the development and maintenance of A.P.I. standards. Others have given the benefit of constructive criticism. The consensus of investigations, analyses, and experiments, together with the experience and judgment of these men, is available in existing specifications, and are a testimonial to the wisdom and effectiveness of the standardization program of the A.P.I. By now the industry generally has accepted these accomplishments and takes them for granted, forgetting the work and effort involved in their development.

In a recent letter to members of the A.P.I. Division of Production, J. Edgar Pew, chairman of the A.P.I. Central Committee on Standardization, remarked: "The war found the oil industry well prepared from the standpoint of standards and simplification of oil field materials, as evidenced by the A.P.I. standardization program and the use of its standards by the armed forces." In support of this statement, the Dallas office of the Institute has received innumerable requests for A.P.I. specifications from Army and Navy officials and from contractors on war work, situated in almost every major city in the United States and from many of the foreign countries where our armed forces are operating.

WPB National Emergency Steel Specifications (NESS) Project. The A.P.I. Division of Production has been in active coöperation with the War Production Board in establishing National Emergency Steel Specifications by nominating representatives of the petroleum industry to various technical advisory committees.

Late in 1941, but before Pearl Harbor, the War Production Board, then the Office of Production Management, requested the assistance of the American Society for Testing Material, Society of Automotive Engineers, and the American Iron and Steel Institute in establishing a series of National Emergency Steel Specifications, to be used for the purpose of increasing the country's output of steel and its products, and conserve critical alloys in the interest of national defense. These organizations agreed to give all possible effort to this end and a committee, with the administrator as chairman, was appointed, being composed of representatives of each of the three national technical organizations, and of the War and Navy departments. The functions of this committee were:

1. To designate and approve of the membership of the various technical advisory committees that would perform the actual work of developing the emergency specifications.

2. To assign the work to the appropriate committees.

3. To review and correlate the reports and recommendations of the technical committees.

4. Plan and guide the entire project and assume the responsibility of selecting a minimum number of steel compositions that would satisfy the specifications selected.

5. Report the recommended list of National Emergency Steel Specifications to the War Production Board.

In selecting the minimum number of steel specifications from those existant, including those of the War and Navy departments, the degree of scarcity of critical materials and alloying elements, and the need for conserving them for the greatest benefit, was to be given considerable thought. Although simplification or streamlining of steel specifications was of first importance, a reduction in the number of sizes and shapes of steel products was also an essential part of the project.

Members of the petroleum industry were nominated on the following:

TAC Nos. 1 and 2, Carbon and Alloy Steel Plates:

Because of the urgency of establishing war emergency specifications for this material, these committees were among the first appointed. Their reports have been submitted to the WPB and approved. The adopted specifications include A.S.T.M. A-7 and A-10, which are cited in A.P.I. tank standards 12-A Riveted Tanks, and 12-C Welded Tanks as governing quality of material.

TAC No. 4, Structural Steel Shapes:

Report of this committee included A.S.T.M. Specification A-7, "Structural Steel for Bridges and Buildings," and A.S.T.M. Specification A-94, "Silicon Structural Steel." These specifications are cited in A.P.I. Derrick Standards as controlling the quality of material. It was also recommended and approved that production of structural steel shapes be restricted to those listed in American Iron and Steel Institute publication, "National Emergency Steel Specifications—Simplification of Structural Steel Shapes," as revised May 11, 1942.

TAC No. 7, Carbon and Alloy Steel Bars, Blooms, Billets, and Slabs:

This committee consists of several sections including one on oil tools and drilling equipment. It has been assigned

*Presented before Mid-Continent District American Petroleum Institute Division of Production, Spring Meeting, Tulsa, Oklahoma, May 20 and 21, 1943.

the work of selecting from specifications promulgated, the minimum number of steel compositions that will satisfy the oil industry's need of raw material that is used in the manufacture of rotary and cable-tool drilling equipment, oil-well pump parts, sucker rods, etc. The membership includes representatives of oil-field equipment manufacturers and also of consumer interests.

TAC No. 11, Tubular Steel Products:

This committee consists of several sections, covering all types of industrial pipe, and including one for oil country tubular goods. Virtually all of the members of this latter section are also members of A.P.I. pipe committees. Its recommendation to the War Production Board included the revised and simplified A.P.I. Standards 5-A Casing, Tubing and Drill Pipe, and 5-L Line Pipe, together with A.S.T.M. specifications A-139 Electric Fusion Welded Steel Pipe, and A-211 Welded Steel or Iron Pipe. Limitation Order L-211 will govern the manufacture of all pipe in accordance with adopted specifications. Certain schedules have been issued as part of this order, including Schedule 9, Oil Country Tubular Goods, effective April 30, 1943. This restricts the manufacture of casing, tubing, and drill-pipe items to A.P.I. standards 5-A, with certain exceptions and provisions.

TAC No. 17, Steel Bars, Forgings and Castings for Pressure Vessels and Pressure Piping:

This committee is charged with the designation of specifications on bolting material, forgings and castings, which activity affects the Institute's standards on steel valves and flanges. The various members of A.P.I. standardization committees are included in the membership.

A.P.I. Standards Program

Let us consider the existing A.P.I. standards from the standpoint of the foregoing remarks.

These now embrace nine main classes of oil-field equipment covering most of the principal items used in drilling, production, oil storage, and transportation. Some of the 29 individual specifications or standards are dimensional only, some cover chemical or physical properties. Others cover all. Many of the specifications include instructions and procedure for testing and inspecting. There are also 13 codes covering recommended practice in field care and use of certain types of equipment. None of the requirements interfere with individual initiative by limiting design details or preventing progressive ideas, and all tend to increase the service life of equipment and prevent undue necessity for replacement.

A.P.I. Belting Standards (Committee No. 1). This covers the tensile strength, elongation, general construction, and definite methods of testing and inspection for seven different types or classes of flat belting. Dimensions of V-belts and V-belts sheave grooves, together with recommendations for power applications, are included. There is no doubt that the industry is provided with adequate belting specifications and that these standards have brought improved service in oil-field applications. Despite the rubber shortage, there are no changes contemplated at present. The recommendations for the care and use of oil-field belting are essentially important from the standpoint of conservation under present conditions.

A.P.I. Oil Field Boiler Standards (Committee No. 2). This specification is unusually effective as boilers must be built in accordance with the A.S.M.E. boiler code as well as meet A.P.I. requirements and use materials with chemical and physical properties required by the A.S.M.E. code. Seven sizes are considered standard and are considered to be sufficient for existing oil-field requirements. No further simplification seems required at this time. By specifying the size of stacks and fittings, interchangeability is assured. Very complete instructions for the care and use of oil field boilers are given in Oil Field Boiler Code No. 2.

A.P.I. Dimensional Standards for Cable Drilling Tools (Committee No. 3). These are principally dimensional standards applicable to tool joints, rope socket necks, jar diameters, etc. Fourteen standard sizes of cable-tool joints are listed in contrast to more than 300 sizes previous to standardization. Information is given on basic thread forms, method of turning the thread, gauging boxes and pins, inspection, and gauges. Dimensions are set up in suitable tables so that interchangeability is assured if the standards are followed. This is a good example of controlling interchangeability but leaving the actual design details to the manufacturer. No further action relative to these specifications is contemplated at present.

A.P.I. Standard Rigs and Derricks (Committee No. 4). This covers major dimensions, chemical and physical properties of materials, allowable working stresses, and also gives formulas for determining the rated load capacity of derricks and related parts. The specification provides for nine standard height-and-base sizes of derricks as standard, in comparison with more than 200 sizes prior to standardization. Overall dimensions are given as well as dimensions and clearances for individual parts such as gin poles, window openings, head board gauges, corner foundation pole settings, etc. Further data are included on two types of derrick substructures, standard rig parts, pumper structures, and other accessory equipment. This set of specifications is very complete and detailed with the result that capacity ratings are determined on a comparative basis.

As a coöperative war effort, Committee No. 4 has inaugurated studies intended to conserve material and simplify stocks and manufacturing operations as follows:

1. The simplification of derrick sizes, by deleting three A.P.I. height-and-base sizes, retaining six sizes as standard.

2. Simplification of pumper-structure sizes by establishing a series of A. P.I. capacities. This study, in coöperation with the A.P.I. Committee on Pumping Equipment, will also include speed reducers.

3. Establish standard dimensions and minimum load requirement of portable drilling and production masts with the intention of improving design and simplifying the numerous styles and sizes currently produced.

A.P.I. Tubular Goods Standards (Committee No. 5). Standards for casing, drill pipe, and tubing, and also for line-pipe, principally cover dimension and physical properties, although certain chemical limitations are stipulated. Gauges and gauging practices are included. In addition, this committee has also formulated standards covering threads in fittings; and the major dimensions, physical and chemical properties and pressure rating of pipe-line valves, production valves, and ring-joint flanges.

The most important accomplishments through standardization of pipe have been interchangeability and improvement in basic properties. Establishment of standard gauge sizes, improvement in threading practices, and the final adoption of what is commonly known as eight round thread has not only provided interchangeability, but has resulted in a threaded joint that gives faster running time, will wear better, and provides a tight joint even after being re-run several times. Trouble with threaded joints, as formerly experienced, has been practically eliminated. It was not so many years ago that pipe supplied for casing was inadequate, even for the comparatively shallow well depths then being drilled, and frequent failures resulted. Today the physical properties of casing produced under the A.P.I. specifications will amply fulfill any requirement, and the user knows more about what to expect of it in performance than ever before. Not only are present materials superior, but the cost per foot of casing for deep wells is now cheaper than that for shal-

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low wells 20 years ago. To use a specific example: casing for a 9460-ft. depth can be purchased for 5 cents per ft. less than that then used for a 3851-ft. string, even if the most expensive grade is used from top to bottom in the deeper string, which is a practice seldom followed today.

Changes made recently in A.P.I. pipe standards, contributory to the war effort, include the following:

1. Simplification of casing lists, reducing the number of items from over 250 to 95.

2. Inclusion of internal upset end casing, which gives full joint strength with a minimum amount of steel.

3. Simplification in plain-end line pipe lists, reducing the number of sizes from 16 to 14, and the number of weights from 121 to 105.

4. Manufacture of seamless and electric weld casing, tubing and line pipe from acid-Bessemer steel, electric furnace steel, and open hearth iron.

In a paper read before this Mid-Continent District Meeting in 1942, entitled "A.P.I. Simplified Casing List," the use of combinations of items in the design of casing strings was urged in the interest of steel conservation. This cannot be too strongly emphasized. However, present delivery conditions do not always permit the full exercise of this principle, even with those who make it a regular practice. The establishment of relatively small stock piles at the mills or other key points would assist in promoting such usage and be more than justifiable by the tonnage of steel which would ultimately be saved. There has recently been some discussion along this line between government and industry representatives.

The selection of the smallest casing size practical for the operation is also a conservation measure of primary importance.

The A.P.I. casing standards provide all items necessary to meet these essential principles of design.

Rotary Drilling Equipment Standards (Committee No. 7). Specifications dealing with transmission specifications such as shafting, keys and pins are dimensional only. Specifications for rotary drilling tool joints are dimensional and include gauges for seven sizes in each of three styles (regular, full-hole, and internal-flush), for use on seven sizes of internal and external upset drill pipe. Those seven standard A.P.I. sizes replace several hundred types and sizes previously in use. There are also standard dimensions for drill collars, fishtail bits, grief stems, rotary drilling hose, piston rods, and lines for slush pumps, and brake bands. Although these specifications insure interchangeability of the items mentioned, freedom in design and arrangement remains. An example of the indirect benefit of the simplified casing list is found in the fact that bit manufacturers have been able to reduce the number of different types and sizes of rock bits by 135 items out of a total of 937 previously required.

A.P.I. Wire Rope and Manila Cordage Standards (Committee No. 9). The main purpose of the specification is to provide uniformity in material and strength within the limitation specified for various grades of wire rope. Tensional strength, methods of testing, tolerances and torsion requirements for wire are included. A very important appendix deals with field care and use, working loads, splicing, field troubles and their cause. Recently the committee has undertaken a revision of the specification to include a readjustment of strength values, where necessary, and to simplify sizes in order to obtain agreement with a "Simplified Practice" on wire rope, prepared in 1942 at the request of the WPB by the National Bureau of Standards in collaboration with the Wire Rope and Strand Manufacturers Association.

The committee is now conducting an extensive survey of oil-producing interests to determine what action should be taken regarding the specification on manila cordage because of the scarcity of this material as a result of the war, and oil country drilling requirements having caused cordage manufacturers to deviate from A.P.I. specifications during the last several years.

A.P.I. Pumping Equipment Standards (Committee No. 11). This series of standards amply handles a very broad subject. It includes oil-well pumps, sucker rods, internal-combustion engines for oil industry use, miscellaneous pumping equipment, gear and roller chain speed reducers, sucker rod and tubing hoisting equipment.

The oil-well pump specifications include dimensional standards for practically all types of reciprocating pumps, grouped into a series of parts elements to provide for interchangeability. These standard dimensions are being followed, but the marking system is not in general use and should be promoted by operators, in order to supply more incentive to the manufacturers and suppliers to follow it closely. Operators using the marking system state that it is easy to handle after being put into practice, although it seems complicated. No attempt is made to consider chemical or physical properties and therefore the manufacturers have ample opportunity to use their individual ideas and designs. Information is included on the care and use of such pumps.

Practically the same type of information is given for sucker rods, with particular attention paid to threads, gauges, and gauging. By this standardization much needed interchangeability was assured, and a great many types and combinations have been eliminated. Interchangeability is provided on polished rods, stuffingbox bores, and pull rod couplings. A simplification program for sucker rod specifications has been completed, which is intended to reduce the amount of raw stock needed by sucker rod manufacturers by as much as 50 percent. This will also include polished rods.

Specifications covering internal-combustion engines for oil industry use carefully avoid interfering with fundamental design and yet provide a method of rating that affords the purchaser a uniform basis for comparing various engines with respect to power capacity, fuel economy, speed range, and coefficient of fluctuation. This does not include maintenance and durability factors. Clutch and fly-wheel connections, together with exhaust and intake connections, are also standardized. Rules for inspection are given and a code is available for the installation, operation and care of such equipment. This information has been badly needed in the past and, when utilized with dimensional data, will prevent many engine misapplications.

In the specifications for steel gear and roller chain speed reducers, dimensional data is omitted but a method of rating the various reducers is provided. Work is being carried on by the committee that may ultimately provide a simplified series of sizes. The specifications also enter into the design of housing, shafts, and bearings, and give rules for calculating the respective loads to arrive at the ultimate A.P.I. ratings. Sections are included to provide means for determining peak torque ratings, well loads, and rules for inspection. The value of these specifications has been proved by the very few reducer failures now experienced in oil-field installations.

The final section in this series of standards provides a method of rating the capacity of sucker rod and tubing hoisting equipment which had been on a very indefinite basis previously.

Considering equipment such as engines, radiator engine coolers, pumping units, belts, etc., it has been seldom in the past that any two manufacturers rated their product in the same manner, which often resulted in misapplication or installation of unsuitable equipment. By following A.P.I. standards, all ratings and capacities are on a uniform basis, which will eliminate these difficulties. The operator should insist that

the manufacturer use the A.P.I. rating method wherever possible.

Standard Tanks (Committee No. 12). These specifications include those for tanks with riveted shells, bolted tanks, all-welded oil storage tanks, and all-welded production tanks. The riveted and all-welded storage tank specifications provide for several economical tanks in a range of sizes that will meet usual needs. Chemical and physical properties of material are included together with a design, fabrication, and erection details. The bolted tank standard is dimensional only, providing an adequate range of sizes to be built in accordance with good manufacturing practice, so that decks, bottoms, and individual staves are completely interchangeable. The specifications for all-welded tanks cover an adequate range of sizes and provided information on material, plate thickness, design factors, clean-out plates, walk and stairways.

This committee has completed the formulation of standards for wooden tanks, as a possible aid to the war effort. A specification for reinforced concrete oil-storage tanks was worked on at some length and dropped to avoid duplication of effort, as another organization has published data on such tanks.

It should be kept in mind that the economic policy on which standardization is based demands low ultimate costs, which are often synonymous with the lightest weights and lowest grades that produce a maximum saving in steel and alloying materials. Savings in steel and alloys have been accomplished for years by saving money through proper engineering design.

To destroy the results of experience that have accumulated in the A.P.I. standards by lowering their quality is not only unnecessary but dangerous. If we cannot get a certain critical material required by these standards, or if it is definitely known that the war effort will be assisted by not using it, this should be done outside of the standards, allowing them to be maintained on their present high plane. To try to change steel specifications to meet conditions would create a continual state of confusion. This is illustrated by the steel alloy situation. Yesterday nickel was scarce and molybdenum was more readily available. Today molybdenum is also scarce and new steel specifications must again be worked out.

Standards make specifications applicable to many manufacturers, permitting a choice as to source of supply. Deviation from this raises the cost of the product in both material and man-hours, and would often create the necessity for new tools, gauges, and equipment. The interchangeability feature of standards also assists the inexperienced labor problem.

Lowering quality of product may result in inadequate material, which would create physical waste of more material than had been saved. There is a possibility that the oil industry may be called upon to produce to capacity before the war is over. Therefore, it seems advisable to maintain the present quality of equipment installations in order that this may be accomplished.

Most of the possibilities for conservation of material lie in application by the operator and not in change in standards. It is the responsibility of each to see that these possibilities are fully utilized.

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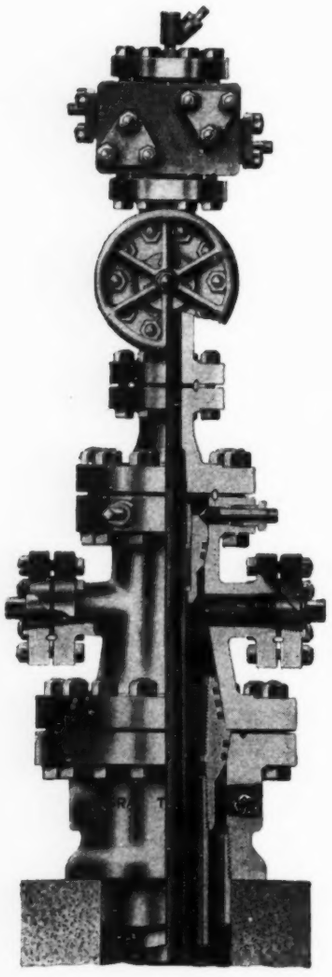

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A Review of Recent Advances in Drilling Mud Control*

By
PRESTON E. CHANEY
Sun Oil Company

Abstract

A GENERAL review of the colloidal chemistry of clays and shales is presented as a theoretical background for the explanation of the various mud problems, and for the chemical treatments used in their correction.

Each of the common mud problems is discussed separately, and an attempt is made to provide a method of diagnosing the cause of trouble from changes in the physical properties of the mud. Following this diagnosis, one or more methods of treatment for correction of the trouble are described, and the theoretical explanation for the action of the corrective treatment is presented whenever possible.

A table showing the combinations of mud properties, or "symptoms" associated with each type of trouble, together with an outline of the corrective treatment, is presented as an aid in rapidly deciding upon the cause of trouble and in selecting the proper treatment.

It is urged that more effort be applied to determination of the cause of mud trouble. A careful study of the results of the various field mud tests is ordinarily sufficient to indicate the impurity producing trouble, and a method of treatment that eliminates this impurity will give better and more economical results than are obtainable by a trial-and-error treatment to improve certain physical properties of the mud.

Introduction

In recent years the technique of mud control has made rapid advances. The research engineers of the oil industry, of the universities, and of the commercial mud and chemical companies have sought and found explanations for many of the peculiarities of mud behavior. Consequently they are able to predict more accurately than before the response of mud to various treatments and, in many cases, to avoid trouble as well as to correct it.

Unfortunately, the field mud engineer often does not have the opportunity to study the literature and to perform the experiments necessary to a practical field application of these new discoveries. Consequently there is a gap between the research departments and field practice that delays the advance in field mud-control technique. To the practical mud engineer, the research man often seems too theoretical, and to the research man, the field engineer seems unwilling to accept new ideas. However, it is necessary to efficient operation that these groups coöperate.

In this paper an attempt is made to bridge this gap between laboratory and field practice. The ordinary mud troubles are considered, and an effort made to explain theoretically both the cause of the trouble and the effects of the corrective chemical treatment. The paper has been written primarily from a practical standpoint, and to the research engineer the theoretical phases probably will appear overly simplified. Most controversial points of theory have been omitted in order to avoid confusion, and only those theoretical explanations that, in the author's opinion, best seem to fit the facts are included. All methods of mud treatment suggested in the following paragraphs have been used successfully and economically in the field.

It is realized in presenting this paper that criticism will come from both research and field engineers, for the reason that a compromise between the two points of view has been attempted. However, if the paper serves to draw these two groups nearer to mutual understanding, and to further the application of fundamental colloid chemistry in the analysis and treatment of field mud problems, it will have served its purpose.

Daily Field Tests

The following tests are essential to any proper estimation of mud condition. They should be conducted daily, or more often in case of trouble. A suitable form, or a place on the daily drilling report, should be provided for reporting the results of these daily tests:

1. Weight (lb. per gal., lb. per cu. ft., or lb. per sq. in. per 100 ft. of depth).

(Note: Hydrometer or balance should be adjusted to the calibration mark with water at least once per day when weight is critical.)

2. Viscosity (Marsh-funnel) (in seconds).

(Note: When commercial weighting materials are used, and in all deep drilling, weight and viscosity should be determined at frequent intervals.)

3. Sand and total solids (percent).

(One sample from pump suction, and one from flow line.)

4. pH.

5. 30-min. filter test:

   a. Record milliliters of filtrate at end of 30 min.
   b. Record cake thickness (32nds of an inch).

6. Salt—reported as parts per million of chloride.

7. Remarks:

In the daily report, under "remarks," record any mud properties such as high gel rate, gas bubbles, etc., which may be observed from the general appearance of the mud, but which are not indicated directly by the foregoing test results. Also note any tight sections in the hole or other drilling difficulties that might possibly be corrected by suitable adjustments of mud properties.

The American Petroleum Institute has recommended standard methods of conducting the foregoing tests, and detailed procedures may be found in their publication entitled *A.P.I. Code No. 29: "Recommended Practice on Standard Field Procedure for Testing Drilling Fluids," second edition (1942)*

Colloidal Clays and Shales

Inasmuch as such a large proportion of all mud troubles is of chemical origin, it is essential that the field engineer have a working knowledge of the chemistry of colloidal clays. The following discussion of colloidal-clay chemistry is presented only as a review or survey of the literature. For a more complete study of this subject, the reader is referred to the list of references at the end of this paper.

Hydration of Clay Colloids

Colloidal materials may be divided into two general types, according to their action when suspended in water:

The suspensoids, or hydrophobic colloids, have little affinity for water, and only form a stable suspension if the individual particle charge is sufficiently high to prevent coagulation. Such colloids do not swell in water. The emulsoid or hydrophilic colloids, on the other hand, have a strong affinity for water. Each emulsoid particle "hydrates," or sheaths itself in a protective film of water molecules, and a noticeable swelling of the clay particles results.

The bentonitic-clay colloids belong to this latter class, and most of the common mud troubles are caused by undesirable reactions involving these clay colloids. The bentonitic clays and shales are micaceous in structure; i.e., the individual clay particles are thin flat sheets, stacked in mica-like layers. On one of the flat surfaces of these individual leaflets are attached cations,

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such as Na^+, H^+, Ca^+, etc. The opposite surface, due to internal structure, is slightly negative with respect to the surface bearing these cations. Consequently there is a weak electrostatic attraction between opposite faces of adjacent particles that serves to bind the plates together.

This bonding force is so weak that water molecules may enter and spread the plates apart. This process is responsible for the swelling of the clay, and the "planar water" so attached comprises a large part of the total water retained by the clay colloids.

This planar water is held in place by the weak residual electrostatic forces of the clay particles. These forces increase with increasing ionization of the clay particles; and it is, therefore, to be expected that the degree of swelling and the amount of water retained by the clays should vary according to the particular alkali or alkaline-earth metal present. The relative degrees of ionization of the more common clay salts decrease in the order Li, Na, K, NH_4, Mg, Ca, Sr, Ba, H, according to Jenny and Reitemeier.[1] Consequently the degree of hydration and the relative stability of the clays decrease in the same order. This means that, for a given clay concentration, a clay containing sodium ions will swell more in water and will have greater stability in general than a clay in which the sodium is replaced by calcium or magnesium.

Clays are known by the predominating positive ion as: sodium bentonite, calcium bentonite, etc. The best drilling clays are practically pure sodium bentonites, inasmuch as these clays can retain relatively larger quantities of water and are more stable and more readily dispersed than the alkaline-earth clays, such as calcium bentonite.

Effect of pH Variation

The pH of a solution is defined technically as the logarithm of the reciprocal of its hydrogen-ion concentration. In simpler terms, we may consider pure water, which has a pH of 7.0, as neutral. The addition of an alkali, such as sodium hydroxide, increases the pH, whereas the addition of an acid will reduce the pH. As the pH of a solution is reduced, the solution becomes progressively more acid; and, as the pH is increased, it becomes progressively more alkaline.

Variations in the pH, or hydrogen-ion concentration, of a clay suspension produce corresponding changes in the physical properties of the suspension. The pH of a suspension of pure hydrogen bentonite, as obtained by electrolysis, is in the range of 2.0 to 3.0. If sodium hydroxide be added slowly to this suspension, the pH will increase, and the hydrogen ions will be replaced by sodium ions up to a pH between 9.0 to 10.0. At this point the hydrogen ions are replaced completely by sodium, and the clay is now a sodium bentonite rather than a hydrogen bentonite.

Garrison and ten Brink[2] have plotted the course of viscosity and gel-rate variations with increasing pH in bentonite suspensions. They found that in the range of pH 4.5 to about 10.5 the viscosity at low rates of shear decreased with increasing pH, and that a minimum in both viscosity and gel rate occurred in the range of pH 9.5 to 10.5. However, Garrison[3] has shown that the ultimate gel strength of the suspension increases with increasing pH. Thus an increased pH tends to reduce the gel rate, but increases the gel strength; whereas a reduction in pH produces the opposite effect. Hence, to a certain extent, it is possible to adjust the relationship between gel rate and ultimate gel strength by pH control.

The mud pH also has an appreciable effect upon the rate of dispersion of shale colloids into the mud system, as has been demonstrated by Garrison, ten Brink, and Elkin.[4] Under the influence of fluid motion the rate of dispersion of shales into the mud stream increases with increasing pH. Therefore, it is possible to increase the yield of natural mud from the shales drilled by maintaining the mud pH in the range of 9.5 to 10.5, rather than in the more usual range of 8.0 to 9.0. On the other hand, when heavily weighted muds are used and trouble is encountered from the rapid accumulation of colloidal material in the mud, it is advisable to reduce the pH to a value between 7.5 and 8.0 in order to retard the rate of shale dispersion.

Also, this treatment is advisable when bentonitic heaving shales are encountered, as a low pH reduces the tendency of these shales to swell and heave into the hole. However, low pH values tend to reduce the gel strength of muds below satisfactory limits, and this fact should be kept in mind whenever pH reduction is contemplated.

Viscosity Relationships

There are at least three factors entering into the viscosity-concentration relationship for any given clay suspensions; these are: 1, the mutual repulsion due to particle charge; 2, the degree of hydration of the colloid particles; and, 3, the mutual attraction due to unsatisfied or partly satisfied broken-bond valences.

1. Repulsive forces between clay particles. The bentonitic clays may be considered as salts having a normal positive ion, such as sodium or calcium, but having an extremely large negative ion, consisting of the remainder of the clay particle. These "salts" are ionized to give a positive (sodium, calcium, etc.) ion, and a negative "bentonite" ion. The degree of ionization and, therefore, the effective negative charge on the bentonite particle, depend on the positive ion with which the particle is combined. Thus a sodium bentonite will have a relatively higher negative particle charge than a calcium bentonite because of its higher degree of ionization. This negative particle charge causes a mutual repulsion between the particles, and tends to reduce particle friction and to prevent the formation of aggregates such as are formed when a drilling mud is flocculated by cement. This effect alone would tend to yield lower viscosities in sodium-bentonite suspensions than in calcium-bentonite suspensions of the same concentration, but the expected reduction in viscosity due to greater repulsive forces in the sodium-bentonite suspension is more than balanced by the increase in viscosity due to the higher degree of hydration.

2. Hydration of clay particles. The greater degree of ionization and the greater positive-ion hydration of sodium bentonites cause these clays to swell more and to absorb higher percentages of water than the corresponding calcium bentonites. The absorption of water by the clay particles increases their effective diameter, and at the same time inactivates a portion of the water in which the clay is suspended. Both of these effects tend to increase the viscosity of the clay suspension, and are responsible for the fact that higher viscosities are obtained with a given clay concentration using sodium bentonites than with calcium bentonites.

The stability of colloidal suspensions is due to hydration and to the repulsive forces between the individual colloid particles. Any added impurity that tends to reduce the degree of hydration or the particle charge will reduce the stability of the suspension. Thus, when a salt-water flow occurs, the high salt concentration in the drilling fluid serves to dehydrate the clay colloids and to repress their ionization. This reduces the forces stabilizing the suspension and causes flocculation and settling of the clay colloids.

3. Attractive forces between clay particles. The third factor influencing the viscosity of clay suspensions is that of mutual attraction due to unsatisfied broken-bond valences. As previously explained, the individual clay particles are thin flat sheets, which theoretically could have an unlimited width and length. However, in all natural clays these sheets are broken into sections of very minute width and length. At the surface of this fracture, there are frequently residual valence bonds which originally served to hold

the larger sheets together, but which now are left chemically unsatisfied. These residual valences are satisfied in part by the adsorption of water at the broken surface, but there remains a relatively strong attractive force tending to pull another clay particle into a position such that it will form a continuation of the clay sheet and completely satisfy the residual valences of both clay particles. This attractive force between the particles tends to increase the friction between them, and thus increases the viscosity of the clay suspension. Furthermore, when the clay suspension is allowed to remain quiescent for a short time, the particles tend to arrange themselves in a definite pattern and to resist any force tending to destroy this pattern. This latter effect is responsible for gelation, and will be discussed more fully in a subsequent paragraph.

Viscosity-Reducing Chemical

The primary effect of viscosity-reducing chemical is believed to be a neutralization of these residual broken-bond valences. By the absorption of certain negative ions at the broken-bond surface, these residual valences are satisfied almost completely. Among those negative ions preferentially adsorbed at the broken-bond surfaces are the tannates, gallates, and the complex phosphate ions, such as hexametaphosphate, pyrophosphate, and tetraphosphate. The adsorption of these ions at the broken-bond surface alters the balance of forces acting between the clay particles from a preponderantly attractive force, due to these residual valences, to a preponderantly repulsive force, due to the normally weaker negative particle charge produced by ionization. As the forces acting between the particles are now preponderantly repulsive, the particles tend to avoid contact with one another. Particle friction, and the tendency to form gel structures, thus are reduced, with a consequent reduction in the viscosity of the clay suspension, or drilling mud.

Gelation

The gelling qualities of a clay suspension are dependent upon the relative attractive and repulsive forces between the clay particles. If the attractive forces due to residual valency are strong and the repulsive forces due to ionization are weak, the mud will have a high gel rate and gel strength. On the other hand, if the repulsive forces are strong, and the attractive forces are weak, the mud will have a slow gel rate and a weak ultimate gel strength.

Any change that tends to alter the relationship between these attractive and repulsive forces will have a pronounced effect upon the gel characteristics of the mud. The addition of small quantities of soluble calcium salts or relatively larger quantities of sodium salts reduces the degree of ionization and, therefore, the negative charge on the clay particles, without materially changing the attractive forces. Consequently the gel rate and gel strength of the mud will be increased. On the other hand, the addition of a complex phosphate, for example, will neutralize the residual broken-bond valences without appreciably reducing the ionization of the clay. Hence the attractive forces are reduced in proportion to the repulsive forces, and a reduced gel rate, gel strength, and viscosity result. In some cases it is difficult to control viscosity by chemical treatment without undesirable reduction in gel strength. Loomis, Ford, and Fidiam[5] have suggested that under such conditions sodium chloride be added to the mud. The addition of moderate amounts of salt (sodium chloride) reduces the repelling forces between the clay particles, by repressing the ionization, and tends to increase the gel strength. However, this treatment has not been used in the field by the author.

A careful study of the theoretical explanations of mud behavior is helpful to an understanding of the "why" of various mud-treatment methods, and assists in a determination of the proper procedure in handling unusual mud problems.

Common Mud Troubles

The author's experience indicates that, in general, each mud trouble produces certain definite changes in the mud properties that are characteristic of that particular trouble. Therefore, it is usually possible to "diagnose" the cause of any given mud trouble from a careful study of changes in the various mud properties produced by it. In this connection it is important to note that changes in the mud properties, rather than their actual values, are used in this diagnosis. The actual values obtained at any one time from the usual mud tests are important to the drilling operation, but often are not sufficient to enable the engineer to diagnose properly the cause of mud troubles. For example, it is possible to produce a very satisfactory mud having a chloride concentration as high as 5000 p.p.m. However, if we start with a mud having a chloride concentration of 1000 p.p.m. and suddenly increase the concentration to 5000 p.p.m., the water loss, gel rate, gel strength, and viscosity will increase beyond satisfactory limits, and the treatment described in following paragraphs for high salt concentrations will be necessary in order to recondition the mud.

In the following paragraphs an effort is made to outline the changes in mud properties characteristic of the various troubles, and to explain the chemical treatments used for their correction after the proper "diagnosis" has been made.

Cement Contamination

One of the most common mud troubles is cement contamination. Usually no "symptoms" are required to locate this trouble, because it may be expected whenever operations require that cement be drilled, and particularly when the cement has not set thoroughly.

Effect of cement on clay colloids. Calcium hydroxide (slaked lime) is present in cement slurries, largely as a result of the hydrolysis of various alkaline calcium silicates and aluminates. The calcium hydroxide so formed is responsible for the observed changes in the mud properties. The calcium ion replaces the sodium on the clay particles, thus converting them to calcium bentonite, while the hydroxyl ion produces a sharp increase in the mud pH. As discussed previously, the calcium clays are not so highly ionized as the sodium clays. Consequently the degree of hydration and dispersion of the clay colloids is reduced. This accounts for the increase in water loss resulting from cement contamination. A further effect of the calcium ion is a flocculation of the clay colloids: i.e., the colloid particles are caused to combine into aggregates of much larger size. Flocculation is responsible for the high viscosity and gel rate of cement-cut muds. The increase in pH, due to the hydroxyl ion coming from the slaked lime, tends to increase further the gel strength of the mud, and thus adds to the trouble.

Corrective chemical treatment for cement contamination. In treating a cement-contaminated mud we must accomplish the following results:

1. Remove the calcium ions as an insoluble precipitate.
2. Reduce the pH to approximately the value before contamination.
3. Redisperse the clay aggregates as much as possible.
4. Replace with fresh clay any colloidal material that cannot be restored readily to its original condition.

In practical application, the first three of these aims are accomplished simultaneously, whereas the fourth is not usually begun until the pH has been reduced to its proper value.

The first treatment consists of a mixture, in about equal proportion, of monosodium orthophosphate and one of the complex phosphates, or of sodium acid pyrophosphate used alone. The complex phosphate acts as a dispersing agent to break up the clay aggregates, whereas the monosodium phosphate re-

moves the calcium and reduces the pH according to the following chemical reactions:

$$(1)\quad 3\,Ca(OH)_2 + 2\,NaH_2PO_4 \rightarrow Ca_3(PO_4)_2\downarrow + 2NaOH + H_2O$$
$$(2)\quad NaOH + NaH_2PO_4 \rightarrow Na_2HPO_4 + H_2O$$

The first of these reactions is complete before the second begins. It will be observed that sodium hydroxide (caustic soda) is a product of the first reaction and, as this compound is a strong alkali, the pH will not be reduced materially until this reaction has been completed and the second begins. Therefore, by watching for a sharp change in the pH we can tell when all calcium has been precipitated. At this stage in the treatment, the mud usually has a satisfactory Marsh-funnel viscosity—although the viscosity is sometimes even lower than desired, but the rapid gel rate makes the mud appear to have a much higher viscosity, and the high water loss remains unchanged. Addition of fresh bentonite may be begun at this stage if the water loss is exceptionally high, but usually it is better to reduce the pH to its original value by continued use of monosodium phosphate (with only enough complex phosphate to maintain desired viscosity) before clay is added. When the pH has been restored to its original value, the use of monosodium phosphate is discontinued; and, as the final step in the treatment, the ordinary viscosity-controlling agents are used to maintain satisfactory viscosity while the bentonitic clay is being added to reduce the water loss and gel rate of the mud to the desired values.

Pretreatment for cement contamination. When it is known in advance that cement contamination will take place, it is advisable to pretreat the mud with as much monosodium phosphate or sodium acid pyrophosphate as can be added without reducing the pH too low or otherwise damaging the mud. This pretreatment will reduce mud flocculation greatly during cement drilling by precipitating most of the undesirable constituents of the cement before serious damage to the mud has occurred.

Calcium Salts

As mentioned in the section on cement contamination, any soluble calcium salt will cause the flocculation of colloidal clays. In normal drilling, sections of lime or limey shale, anhydrite, gypsum, etc., are encountered. These calcium salts are sufficiently soluble to cause trouble from clay flocculation.

Effect of calcium salts on clay colloids. The characteristics of a mud containing soluble calcium salts depend somewhat on the past history of the mud. One of the peculiarities of clay colloids is the effect of calcium salts on the viscosity. If a soluble calcium salt —for example, calcium chloride—is added to a dry sodium bentonite and the clay then is dispersed in water, the viscosity will be very low for a given clay concentration. On the other hand, if the clay first is dispersed in water and allowed to hydrate, the addition of a calcium salt then will produce a sharp increase in the mud viscosity.

In the first case the clay is converted to a calcium clay before it has had time to hydrate, and the calcium clay does not hydrate so completely as would the sodium clay. Therefore, the clay particles have a smaller effective diameter, and higher clay concentrations would be required to cause the same degree of particle interference in the suspension. On the other hand, if the clay first is hydrated, the individual particles have a large diameter due to the swelling produced by hydration. The addition of calcium then flocculates or coagulates these larger particles, causing them to be attracted by one another. This increases the particle friction, with a consequent increase in viscosity.

Effect of calcium salts on field drilling muds. In drilling a large shale section containing only moderate amounts of calcium and magnesium salts, the mud will be converted gradually to a calcium-bentonite mud as the original clay is deposited as a filter cake on the walls of the bore hole and is replaced by these calcium or magnesium clays. This will result in a decreased mud viscosity, a fast gel rate, and usually a slight increase in the water loss.

However, when large sections of anhydrite or gypsum suddenly are encountered—as, for example, in drilling the cap material on many shallow salt domes—a high concentration of calcium is built up rapidly in the mud. This causes flocculation on the sodium clay present in the mud, and results in an increase of gel rate, viscosity, and water loss. It will be noted that, with the exception of the pH, these are the effects produced by cement contamination; and, as the calcium ion is responsible in both cases, we would expect this similarity in effect.

The first set of "symptoms" of calcium contamination ordinarily is encountered only in shallow drilling, with natural muds containing little or no phosphate. In this case, a limey shale section will be found to produce very little mud. The mud produced will have a fast gel rate and a weak gel strength which prevent the proper settling of sand; the viscosity will be abnormally low; and the water loss usually is moderately high. Furthermore, the presence of excess free calcium in the mud will convert to a calcium bentonite any fresh dry clay added to the mud before the clay has had time to hydrate—which would make it necessary to add excessive quantities of clay to obtain the desired increase in viscosity and reduction in water loss and gel rate.

The second set of "symptoms" will be found on any mud when large sections of soluble calcium salts are drilled, and to some degree in drilling limey shale sections with muds containing high concentrations of good clay (low water-loss muds).

Corrective chemical treatment for contamination by soluble calcium salts. The primary aim of treatment is to precipitate the calcium as an insoluble compound; this may be accomplished by use of disodium phosphate or soda ash, according to the following reactions:

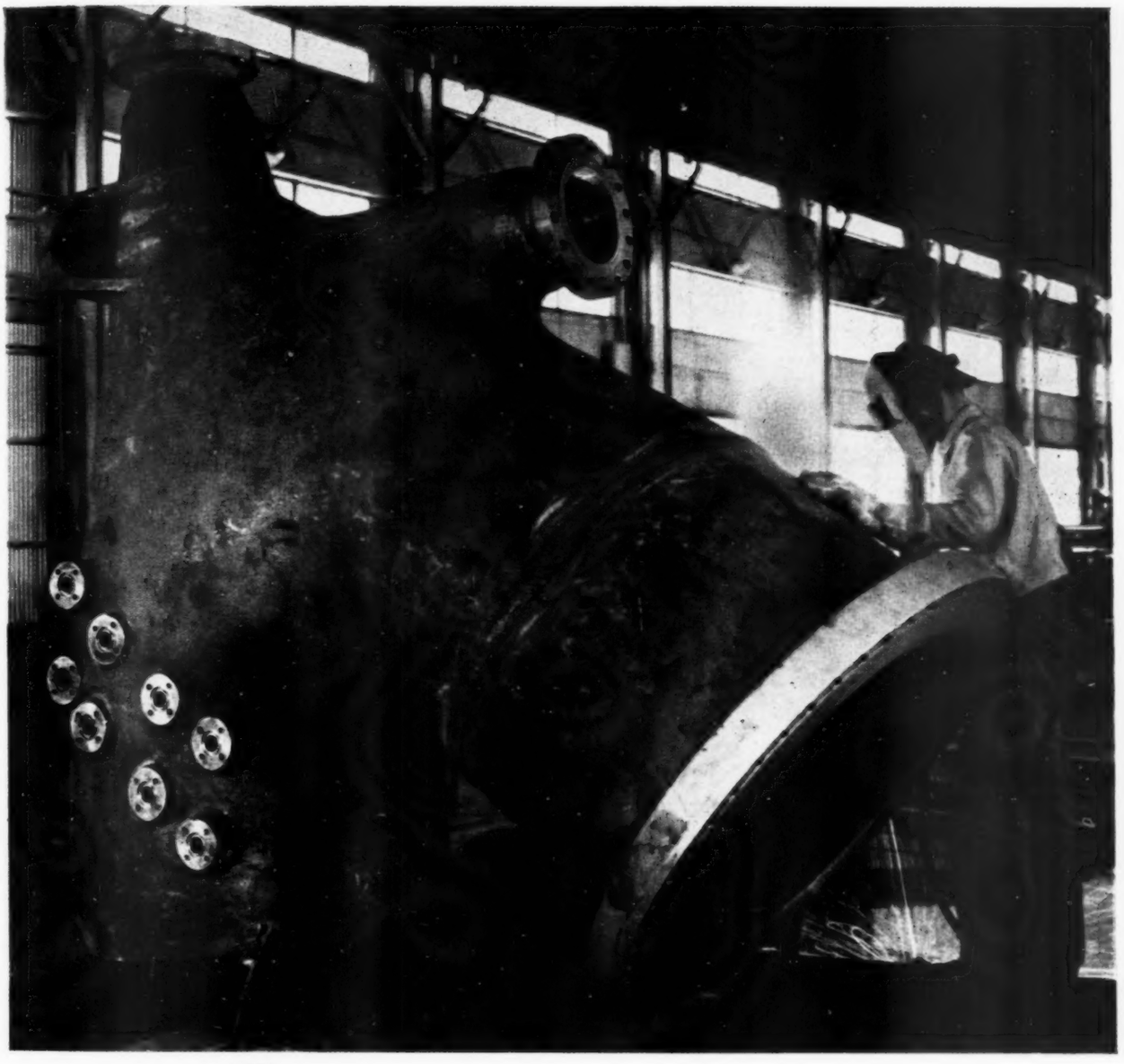
$$(1)\quad CaSO_4 + Na_2PHO_4 \rightarrow \underset{\text{Insoluble}}{CaHPO_4\downarrow} + Na_2SO_4$$
$$(1)\quad CaSO_4 + Na_2CO_3 \rightarrow \underset{\text{Insoluble}}{CaCO_3\downarrow} + Na_2SO_4$$

The choice between these two treating agents is based on the pH of the mud prior to treatment. Disodium phosphate produces little or no change in the mud pH, whereas soda ash increases it sharply. Therefore, disodium phosphate should be used if the mud pH is satisfactory, and soda ash is the correct choice if an increase in pH is desired; monosodium phosphate may be used occasionally if the initial pH of the mud is high.

In this connection, it is advisable to review the foregoing discussion of pH. Usually, in drilling limey shale sections with natural mud, little or no mud is formed from the shale. In order to make more mud from the formation, it is desirable to have the pH in the range 9.5 to 10.0. Therefore, in this case soda ash would be the proper selection.

One of the usual viscosity-reducing chemicals must be used along with the soda ash or disodium phosphate in order to maintain a satisfactory viscosity and to disperse the clay colloids, as these chemicals are not effective in viscosity control.

Particularly in the case of natural muds composed largely of calcium shales it will be found that little change in the mud properties is noticeable until the removal of calcium is practically complete. The viscosity will remain low, and the mud will show a fast gel rate and a weak gel strength, up to the time that sufficient soda ash or disodium phosphate has been added to remove the calcium completely. Sometimes this is discouraging, because treatment may be continued for three or four complete circulations of the mud



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without any noticeable improvement; however, continued use of the calcium-precipitating agent will give the desired results.

An effort now is being made to develop a satisfactory field test for estimating the calcium concentration in drilling muds. The results of this work, if successful, will be published in the near future.

Gas Cutting

Gas cutting is largely a mechanical, rather than a chemical, problem in mud control. The hydrostatic head of the mud column must be slightly greater than the formation pressure at every point in the hole in order to prevent the flow of formation fluid into the mud system. Gas in the mud indicates that the hydrostatic head of the mud is too low to meet this requirement, and the obvious solution is to increase the mud weight by the addition of commercial weighting materials, such as barytes (barium sulphate).

The addition of weighting material should be begun at the first indication of gas cutting. In this early stage the gas bubbles are very small, and do not rise to the surface of the mud. They are seen best by raking the surface of the mud sample and observing closely for bubbles slightly larger than the point of a pin on the freshly exposed mud surface. This simple test should be performed at frequent intervals when the probability of unusual gas pressures exists; and, if the presence of these small bubbles continues for any length of time, the mud weight should be increased until they disappear.

Corrective treatment for gas-cut muds. In combating high gas pressures, the viscosity and gel rate of the mud should be kept low by chemical treatment to allow the gas bubbles to break out of the mud, and the fluid should be run over a shale shaker or baffle arrangement to allow escape of the entrained gas. Furthermore, the mud pits should be stirred by mud guns to remove any gas not removed at the shale shaker, in order to prevent recycling of the entrained gas. Modern equipment makes it possible to shut the well in and discharge the mud through a choke, if necessary; but this choke should be used only if the mud is leaving the well faster than the pumps can handle it. The use of a choke puts back pressure on the pumps, and reduces the rate of circulation. This concentrates the gas in a small volume of mud, and tends to aggravate the condition.

If weighting material is used, it is advisable to mark the mud level in the pit and observe at frequent intervals for any change. The increase in hydrostatic pressure may cause loss of mud to low-pressure formations; if this occurs before the weight is sufficiently high to hold the gas pressure, suitable measures as discussed under "lot returns" must be taken.

Salt Contamination

Occasionally high-pressure salt water or rock salt is encountered in drilling. As the salt concentration rises in the mud, the high concentration of sodium ions represses the ionization of the clays by simple mass action. This destroys the negative charge on the clay particles, and allows the attractive forces to draw these particles together in large aggregates. The first effect is an increase in gel rate, viscosity, and water loss of the mud. Later, as flocculation and dehydration of the colloids continue, the viscosity falls below normal, and the water loss rises in rough proportion to the salt concentration.

Corrective treatment for salt contamination. The chloride test gives a direct "diagnosis" of salt contamination, but the treatment unfortunately is not so easy. In the case of a salt-water flow, the first step in treatment is to increase the mud weight to the point required to stop the flow. This should be done quickly in order to hold the salt concentration in the mud as low as possible. In drilling rock salt, weighting material is, of course, useless in preventing the salt from rapidly building up to the saturation point in the mud, and on the Gulf Coast it is usually necessary to case off any exposed shale sections if more than a few feet of salt must be drilled.

If the salt concentration in the mud can be held below 7500 p.p.m. of chlorides, the use of disodium phosphate or soda ash to precipitate soluble calcium salts present in the salt water is usually helpful in reducing the gel rate of the mud. However, this treatment has little effect at higher salt concentrations.

The addition of large quantities of Quebracho—sometimes as much as 0.5 to 1.0 lb. per bbl. of mud—also is recommended for reducing the high gel rate produced by high salt concentrations, and in this case the Quebracho may be mixed (about 100 lb. per hour) through the hopper in order to reach the required concentration in the mud system as rapidly as possible.

The ability of colloidal clays to withstand the flocculating effect of salt water increases with increasing clay concentration. Therefore, it is desirable to add large quantities of a highly colloidal clay, preferably hydrated in fresh water before addition to the mud. When high salt concentrations are present, there is little danger of adding too much clay, as the salt dehydrates the clays and prevents the rise in viscosity that would result from the addition of corresponding amounts of clay to a fresh-water mud.

Use of organic colloids in salt-water muds. Recently much research has been conducted in an effort to find a substitute for the clay colloids in salt-water muds. Various organic colloids such as starch, sodium alginate, and various water-soluble natural gums have been tried. These colloids are more resistant to salt flocculation, but all are subject to bacterial attack, which reduces their effectiveness and produces objectionable odors in the mud. However, preservatives such as phenol, formaldehyde, creosote, etc., have been used recently with these materials in both field and laboratory tests, with very promising results.

As is evident from this discussion, salt contamination is at present the most difficult of all mud problems. The usual mud thinners are practically useless, and a mud that will "get by" is frequently the best obtainable with present methods of treatment. However, it is believed that organic colloids will offer a satisfactory solution to this problem as additional field experience in their use and control is made available to the industry.

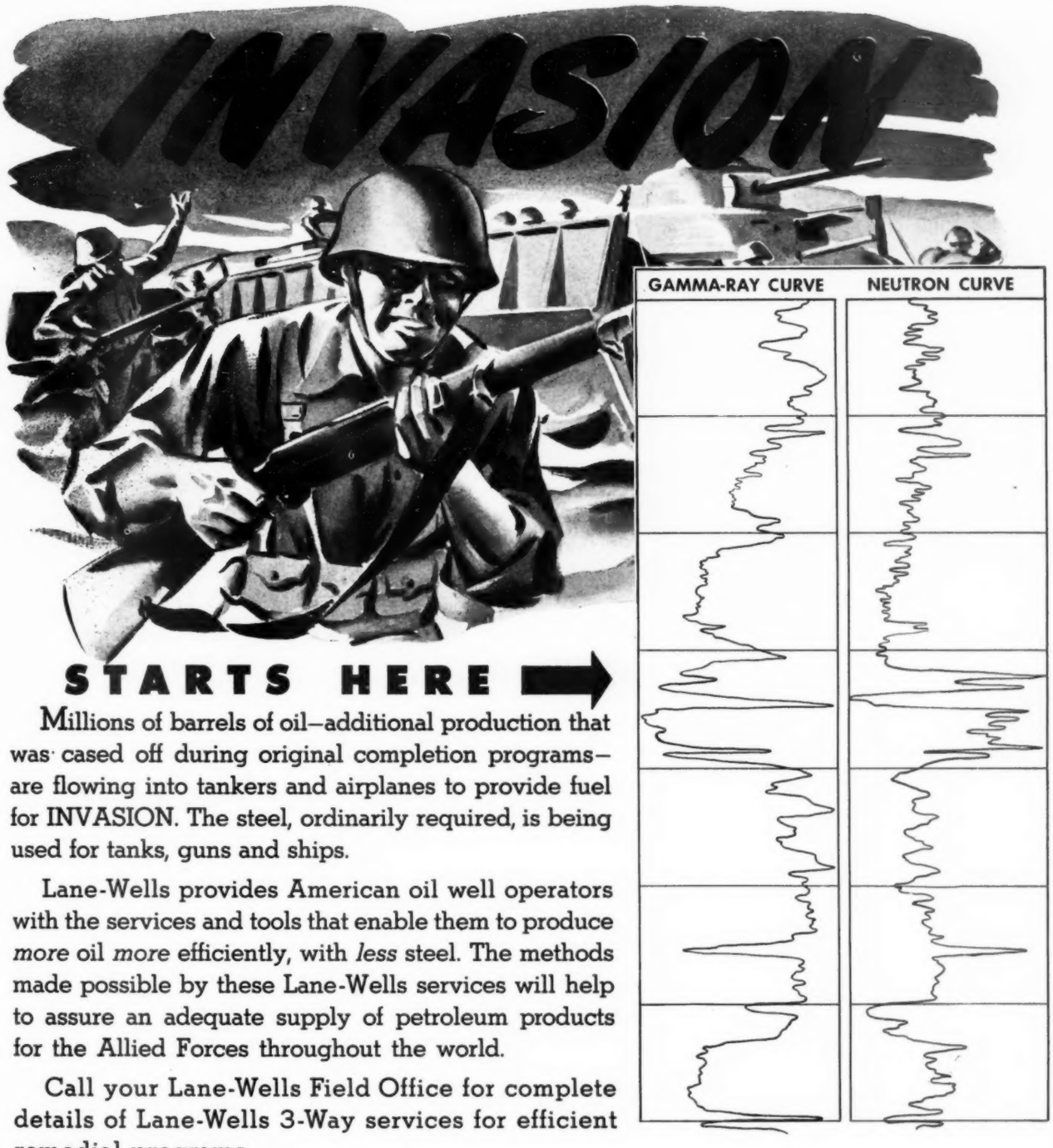
Heaving Shale

There are at least three known types of heaving shale and any number of combinations of these types. They are classified as follows:

1. Shale that swells on absorption of the fluid phase of the drilling mud—usually a highly bentonitic shale.
2. Shales containing small lenticular sands or sandy shales charged with gas at high pressure but low volume.
3. Shale that has been compressed and uplifted to an angle greater than normal dip, and under considerable diastrophic strain.

Control of swelling or bentonitic heaving shale. The bentonitic heaving shales contain clay colloids of the type used in drilling muds. Therefore, any chemical treatment designed to prevent the swelling of these shales is likely to be detrimental to the mud. The presence of bentonitic shale is evidenced by a sharp increase in viscosity and, usually, an appreciable reduction in water loss of the drilling mud. In some cases it is possible to control bentonitic shale by reducing the water loss of the mud to the lowest possible value (less than 6.0 ml) and by the addition of sodium acid pyrophosphate, monosodium phosphate, or some other acidic salt to reduce the mud pH to 7.2 to 7.6. As previously mentioned, the dispersion of clay colloids is delayed by low pH values.

If this treatment is not successful in preventing rapid swelling of the shale, a mud containing sodium silicate and



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saturated salt solution as the fluid phase may be substituted for the normal water-base drilling fluid. The sodium silicate "pickles" the shale, and prevents its swelling or dispersing into the mud stream. Excellent results have been obtained by the use of sodium-silicate muds in several areas where drilling was difficult or impossible with water-base muds.

Control of gas-bearing heaving shale. Shales containing small lenticular sands or sandy shales charged with high-pressure gas are apt to heave unless the hydrostatic head of the mud column is sufficient to balance the gas pressure. This type of shale usually gives the mud a fluffy appearance and a sour-gas odor, but does not change appreciably any of the other mud properties. Tight places in the hole are often the first definite proof of its presence.

The first step in treating to prevent heaving in this type of shale is to increase the mud weight to the point required to exceed the gas pressure in the sandy lenses. This is not always possible, because the gas pressure may be high enough to cause loss of mud to other exposed formations of lower pressure before the hydrostatic head of the mud is sufficiently high to balance the gas pressure. In this event, the mud weight should be maintained at the highest value possible without serious loss of mud.

The mud viscosity and gel strength should be kept low to prevent swabbing shale into the hole as the drill pipe is removed, and in some cases equipment has been used to permit continuous circulation while coming out of the hole, in order completely to eliminate swabbing action.

Drilling under pressure has been tried in a few cases to combat this type of shale, but the expense and mechanical difficulties involved in pressure drilling with equipment now available usually make it uneconomical to drill and produce oil zones requiring this type of drilling equipment.

Control of plastic-flow type of heaving shale. Shale beds that have been uplifted at an angle greater than normal dip, and under present diastrophic strain, are apt to heave, or move by plastic flow into the area of least resistance, i.e., into the drill hole. The movement of these shales is aggravated by the lubricating effect of water from the mud which penetrates along the bedding planes.

To combat this type of heaving shale it is necessary to increase the hydrostatic head of the mud and make it approach as nearly as possible the overburden pressure of the heaving-shale beds. In order to equal the average overburden pressure, a 21.7-lb.-per-gal. mud would be required. This is beyond the range of weights feasible with present weighting materials. Laboratory experiments on the use of galena (a lead ore with a specific gravity of 7.2) as a weighting material indicate that mud weights of the order of 22 lb. per gal are possible, but the high cost of this ore probably will prohibit its use in most cases.

A few successful wells have been drilled through heaving shale of this type by the use of low water-loss muds which weigh from 14 to 18 lb. per gal. Each well of this type is an individual problem, however, and the required mud weight for successful operations depends upon the degree of residual diastrophic strain in the particular area in question. Pressure drilling can be used to advantage in augmenting the mud weight on wells of this type.

Lost Circulation

The loss of mud to the formation is a trouble encountered frequently when cap material on shallow salt domes is drilled, and in normal drilling with heavy muds.

In the case of cap-rock drilling, the cause of lost circulation usually is a cavity in the rock, and usually it is necessary to set pipe through the zone causing trouble—although in some cases it is possible to plug these cavities by use of a quick-setting cement.

In most present-day drilling, however, the mud is lost to a porous low-pressure sand or gravel bed, and it is usually possible in this case to regain circulation by use of various mechanical plastering agents. Among those most commonly used are shredded cellophane, sugar-cane fibers, and mica flakes. These materials are added to the mud in the pit, and are pumped down opposite the zone to which the mud is being lost. Usually best results are obtained by the use of a combination of these materials.

It is necessary to remove the shale-shaker screens or to bypass the shaker in order to circulate these materials; for this reason it is undesirable to leave such materials in the mud for any great length of time. The usual procedure is to drill for 12 to 24 hours after circulation has been regained, and then to remove these materials by means of the shale shaker.

Also, the gel strength of heavily weighted muds should be kept low to prevent breaking down of the formation by the pump pressure required to break the gel and start circulation after a trip. If lost circulation has already occurred or is considered likely, it is advisable, on every trip with the drill pipe, to break circulation one or more times before reaching bottom in order to break the mud gel and reduce the initial pump pressure required to circulate on bottom.

When lost circulation has occurred, it is often possible, by the use of shredded cellophane, mica flakes, etc., to make the formation support a mud weight equal to that which originally caused the breakdown. However, in most cases this mud weight is very close to the upper limit. A small increase in mud weight above this point quite often produces a second breakdown which is more difficult to seal than the first. Therefore, it is advisable to set casing through the zone taking mud if further weight increases are anticipated.

Preventive measures. On the Gulf Coast of Texas and Louisiana there are thick beds of sand in the Miocene, which have been found by experience to take mud under moderate pressures. Consequently, it is advisable to set a protective string of casing through the Miocene sand beds whenever it is necessary to use a mud weighing more than 13 lb. per gal. in drilling the deeper formations.

It also has been found in certain areas where lost circulation in a definite zone has occurred on previous locations that a pretreatment with small quantities of the usual plastering agents is of value. The usual procedure is to add a few hundred pounds of the plastering agent to the mud just prior to drilling the zone in which lost circulation is expected. Circulation of the plastering agent is continued for about 24 hours after drilling the zone, after which the shale-shaker screens are replaced and the plastering material removed.

The explanation offered for this procedure is that it is easier to plaster crevices in the formation before a breakdown occurs than it is to seal off a zone already taking mud. In some cases this procedure seems to have merit. However, it is often not possible to anticipate the occurrence of lost circulation, as is necessary to this procedure.

High-Temperature Decomposition of Phosphates

Many of the viscosity-reducing chemicals now in common use depend for their effect on the dispersing action of the complex phosphates. These complex phosphates are salts obtained from the simple (ortho) phosphates by dehydration. Tetrasodium pyrophosphate, for example, may be produced by the following reaction:

$$2\ Na_2HPO_4 \xrightarrow{\text{Heat}} Na_4P_2O_7 + H_2O$$

Unfortunately, this reaction is reversible in the presence of water, and the rate of reversal increases rapidly with temperature within the range of normal mud temperatures. Hence, in very deep wells, or in drilling near shal-

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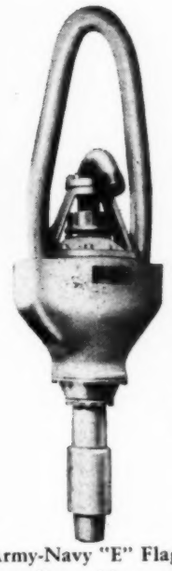

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low salt domes, when abnormal temperatures are encountered, these complex phosphates are decomposed almost completely in one circulation of the mud, and constant additions of relatively large quantities of the complex phosphates are required to keep the viscosity within satisfactory limits. Furthermore, the decomposition products of some of the more common complex phosphates are strongly acidic, and tend to reduce the pH of the mud below desirable limits.

The flow-line temperature may be used as a rough measure of the bottom-hole temperature in deciding when to expect this trouble, as these two temperatures vary in more or less direct proportion. However, the spread between the bottom-hole and flow-line temperatures increases with the depth of the hole. Hence, high-temperature decomposition of the phosphates normally will occur at lower flow-line temperatures on deep wells than on shallow wells. In general, a flow-line temperature of 120°F. or above, indicates a bottom-hole temperature sufficiently high to cause this trouble.

Corrective chemical treatment for high-temperature decomposition of phosphates. In the early stages, a mixture of equal proportions of Quebracho extract and one of the phosphates sometimes will maintain a satisfactory viscosity, and the use of Quebracho has the added advantage of reducing the water loss of the mud. However, Quebracho is capable of reducing the initial and 10-min. gel-strength values so low as to allow settling of cuttings and weighting material on muds having a low pH; and as, the decomposition products of many phosphates tend to lower the mud pH, this mixture must be used with caution. The use of salt as suggested by Loomis, Ford, and Fidiam[5] probably would be of advantage in maintaining satisfactory gel strength under these conditions, but the author knows of no case in which salt has been used.

An organic compound, dicyandiamide, for use in high-temperature muds recently has been placed on the market.[6] This compound, $NH_2C(:NH)NHC\vdots N$, is said to stabilize the phosphates as well as to reduce the viscosity and gel strength of high-temperature muds. As this chemical has been in use only a short time, much remains to be learned of its reactions. However, very satisfactory results have been obtained by its use in combination with the phosphates and Quebracho on some of the deep wells recently drilled on the Gulf Coast of Texas and Louisiana. The procedure recommended by the manufacturers is to add dicyandiamide rapidly to a mud already containing phosphates, up to a concentration of about 0.5 lb. per bbl. of mud, and then to use a combination of phosphates, or Quebracho, and dicyandiamide as required to maintain satisfactory viscosity.

Dicyandiamide, like Quebracho, has been known to reduce the gel strength below desirable limits when too much was used. Therefore, the gel rate and gel strength should be observed carefully during its use.

Phosphorus and the phosphates are used extensively in modern warfare. Therefore, it is quite possible that the industry may be unable to obtain the necessary supply of phosphates for mud control in the future. In that event, it will be necessary to make more extensive use of organic materials such as dicyandiamide, gallic acid, and Quebracho as substitutes for the complex phosphates, and to use sodium bicarbonate or soda ash where we now use the simple orthophosphates.

High Concentration of Colloids

In the course of drilling, beds of bentonitic shale sometimes are encountered which disperse rapidly into the mud system and increase the viscosity and total-solids content of the mud. The rate of dispersion may not be high enough to place them in the class of bentonitic heaving shales, but the accumulation of colloidal material makes viscosity control difficult.

Dilution with water will reduce the viscosity of any drilling mud, and it is, therefore, a temptation for the field engineer to control difficult muds by excessive use of water rather than by proper chemical treatment based on a correct diagnosis of the actual cause of the trouble. Water is a very expensive "chemical" to use on heavily weighted muds. For example, it requires about 600 lb. of barytes to increase the weight of 1 bbl. of water to 16 lb. per gal., whereas the cost of chemicals required to produce the same viscosity reduction is usually much less. We should make certain that the colloid concentration is too high before adding the large volumes of water and weighting material necessary to correct it.

Prevention by pH control. Frequently the high concentration of colloid material may be prevented in part on heavy muds by proper chemical treatment *before* the bentonitic shale is encountered. As mentioned previously, the rate of dispersion of shales into the mud stream increases with increasing mud pH, showing a sharp increase in the range of pH 9 to 11 for most shales. Therefore, it is important in drilling bentonitic shales with heavily weighted muds to adjust the pH of the mud system within the range of pH 7.5 to 8 in order to retard the dispersion of bentonitic shale as much as possible. pH values lower than 7.5 probably would further reduce the rate of shale dispersion, but are not recommended because of the instability of acid muds and the increased corrosion of the drill pipe. A pH range of 8.0 to 9.5 is recommended for all ordinary drilling, but the lower pH values are useful when heavily weighted muds must be used.

Corrective chemical treatment for high concentration of colloids. Muds containing excessive amounts of bentonitic shale will show a high viscosity with *a low water loss.* If the water loss is relatively high, the trouble is probably due to soluble calcium salts rather than to excessive amounts of bentonite, and the treatment should be selected accordingly. The only successful treatment for excessive concentrations of bentonite is dilution with water and the addition of weighting material to maintain the required mud weight. This is an expensive treatment, but is necessary if large sections of bentonitic shale are encountered.

Conclusion

An attempt has been made to rationalize the causes and "cures" of various mud problems on the basis of theoretical considerations. It is believed that a more thorough application of the fundamental principles of colloid chemistry in the field treatment of drilling muds, as opposed to the more common trial-and-error methods of the past, will pay dividends in economical and less troublesome drilling operations.

Often a treatment that gives temporary relief from a particular mud problem may itself cause more serious difficulties at a later date. Therefore, an attempt should be made to look ahead in mud treatment, and to prevent the occurrence of trouble whenever possible. Credit is due the engineer who quickly and economically can correct mud troubles which endanger or delay the drilling operation, but even greater recognition should be given to the less spectacular efforts of those who, by foresight, avoid these costly delays and difficulties.

Closer coöperation between the research and the field engineers is necessary if rapid improvement in field mud-treatment methods and the fullest utilization of research data are to be achieved.

Appendix

The following is an outline of the ordinary mud troubles, their "symptoms," and the methods of treatment most commonly used for their correction. There is included also a list of the most common mud-treatment chemicals, with their pH values in the concentrations ordinarily used in mud

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***Feature* 2 Simplify Operations!** Not only do the Unitized Blocks speed up rig operations by giving more working room between floor and crown, but also eliminate much wasted time changing from one type of equipment to another. **ALL** operations—running drill pipe in and out of the hole, supporting swivel and string while drilling, running tubing, rods, etc.—can be done with the **same** compact unit!

***Feature* 3 Link Adapter is Free-Swivelling!** The link adapter assembly swivels in a complete 360° circle, freely and effortlessly. By means of a unique method of spring-loading the bearing, the link adapter swivels just as easily whether the Block is empty or carrying a full load. Eliminates twisted lines and wasted time!

***Feature* 4 Convenient Built-In Lock!** A locking device is incorporated in the body of the Link Adapter which will lock the unit against rotation in any one of 4 different positions. This speeds up running in the hole by holding the elevators in a pre-determined position for the derrick man... and is useful in many other operations.

***Feature* 5 Rubber Bumper Safeguards Tool Joints!** You can't damage the top of your tool joints by dropping the Block against them because a soft rubber bumper on the bottom of the assembly prevents this. This safety feature is particularly important on portable rig operations where striking the tool joints is almost unavoidable due to the close working space between pipe and Blocks.

***Feature* 6 Detachable Bail for Miscellaneous Work!** Frequently in portable rig operations there are jobs that can be done more effectively with a bail than with the elevators, such as running rods, automatic casing elevators, lifting heavy equipment, etc. For these operations a bail can be quickly attached to the Link Adapter, simplifying this type of work and eliminating the need of changing the unit!

***Feature* 7 A Unitized Block for EVERY Purpose!** So popular have Baash-Ross Unitized Blocks become among operators that we have recently extended the line to include a unit for practically every purpose within the range of portable and slim-hole rigs. The Block can be supplied in 1, 2, 3 and 4 sheave models, each in a choice of 20", 24", 30", and 36" diameter sheaves. This gives a selection of SIXTEEN different sizes—in a capacity range of 30, 65, 100 and 150 tons—a unit to fit practically **EVERY** requirement!

treatment. This list of chemicals was supplied by Arthur G. Levy, of the Fohs Oil Company, and is presented with his kind permission.

Cement contamination

"Symptoms"

1. Increased gel rate and gel strength.
2. Increased pH.
3. Increased viscosity.
4. Increased water loss.

Chemical treatment

1. Mixture of monosodium phosphate and complex phosphate, or sodium acid pyrophosphate alone, until pH returns to value, before contamination.
2. Add colloidal clay slowly, with continued use of complex phosphate to control viscosity, until water loss and gel rate return to normal.

Soluble calcium salts (Lime, gypsum, anhydrite, etc.)

A. In drilling limey shales with natural drilling mud:

"Symptoms"

1. Mud viscosity usually low.
2. Rapid gel rate, weak gel strength.
3. Practically no new mud formed from shales drilled.

Chemical treatment

1. Add soda ash (alkaline), or disodium phosphate (neutral), depending on initial pH, until viscosity begins to rise. There will be little if any improvement in mud properties until treatment is practically complete. Then viscosity and gel characteristics improve rapidly.
2. If gel rate is still too high after viscosity increases to desired value, use mixture of soda ash or disodium phosphate with sufficient complex phosphate to control viscosity until gel rate is satisfactory.
3. Colloidal-clay additions may be required to give satisfactory wall-building characteristics.

B. In drilling beds of gypsum, anhydrite, etc. (large quantities of soluble calcium salts suddenly encountered):

Symptoms"

1. Increased gel rate and gel strength.
2. Increased viscosity.
3. Increased water loss and cake thickness.

Chemical treatment

1. Use mixture of disodium phosphate and complex phosphate to remove calcium and control viscosity.
2. Add fresh bentonite as required to hold required water loss.
3. Quebracho useful in reducing gel rate.

High-pressure gas

"Symptoms"

1. First indicated by minute gas bubbles which do not readily break out of mud. Best seen by raking surface of mud sample and observing for bubbles at freshly exposed surface.
2. More severe stages:
   a. Strong gas odor at flow line.
   b. Gas pockets cause mud to flow by heads.
   c. Distillate forms emulsion with mud, which reduces effectiveness of chemical treatment.
   d. Volume of mud in pit increased just before blowout, indicating that mud is leaving hole faster than pumps can handle it.

Chemical treatment

1. At first definite indication of gas put guns on pit and start mixing weighting material to overcome gas pressure. Increase chemical treatment to reduce viscosity and gel rate of mud. Mark level of mud in pit, and observe frequently for any increase or decrease in mud level.
2. In extreme cases, close blowout preventers and put mud discharge on choke. Choking mud discharge should be done only when absolutely necessary, as this slows circulation of mud and thereby concentrates the gas in a smaller volume.
3. Immediate action is the best solution to gas cutting. Any unnecessary delay in increasing mud weight causes recirculation of gas-cut mud and increases the danger of blowout.

Rock-salt or salt-water flow

"Symptoms"

1. Rapid increase in salt content of mud.
2. First effect is increased gel rate and viscosity. After several hours, or perhaps a day, viscosity drops below normal.
3. Water loss increases rapidly.
4. In case of salt-water flow, mud continues to flow after pumps have been shut down.

Chemical Treatment

1. In case of salt-water flow, increase mud weight as rapidly as possible until shutoff is obtained, but *watch closely* for loss of mud to the formation, and stop weight increase if this occurs (even though some flow of water continues) until mud loss is stopped by addition of plastering agents.
2. In extreme cases, pull up in casing to condition mud, as the danger of stuck drill pipe is serious when salt water is encountered.
3. Add *large* quantities of highly colloidal clay, preferably hydrated in fresh water before addition to the mud.
4. Copious additions of Quebracho are sometimes helpful in reducing salt-water gel."
5. In severe cases, substitute organic colloids for clay in mud.

Heaving shale

A. Bentonitic heaving shale:

"Symptoms"

1. Increase in mud viscosity and gel strength.
2. *Reduction* in water loss and cake thickness.
3. Tight places in hole.

Chemical treatment

1. Reduce water loss to lowest possible value.
2. Reduce mud pH to 7.2 to 7.6 by use of pyrophosphate.
3. Low pH muds tend to have very low gel strength. Do not reduce pH low enough to prevent suspension of weighting material and cuttings.
4. Keep mud viscosity and gel strength as low as possible to prevent swabbing.
5. Use sodium-silicate mud in very severe cases.

B. Gas-bearing heaving shale:

"Symptoms"

1. Sour-gas odor at shale shaker.
2. Little increase in viscosity unless bentonitic shale is also present.
3. Tight places in hole.

Chemical treatment

1. Reduce water loss of mud.
2. Increase mud weight until difficulty is stopped or until loss of mud to formation begins.

C. Plastic-flow heaving shale:

"Symptoms"

1. Large slabs of shale circulated out of hole.
2. Shale may flow into hole to a height of a hundred or more feet on removal of drill pipe.
3. Stuck drill pipe or tight places in hole.
4. Usually found on highest part of structure.

Chemical treatment

Same as for "B".

Cavity, or highly porous formation

"Symptoms"

1. Partial or complete loss of mud returns.

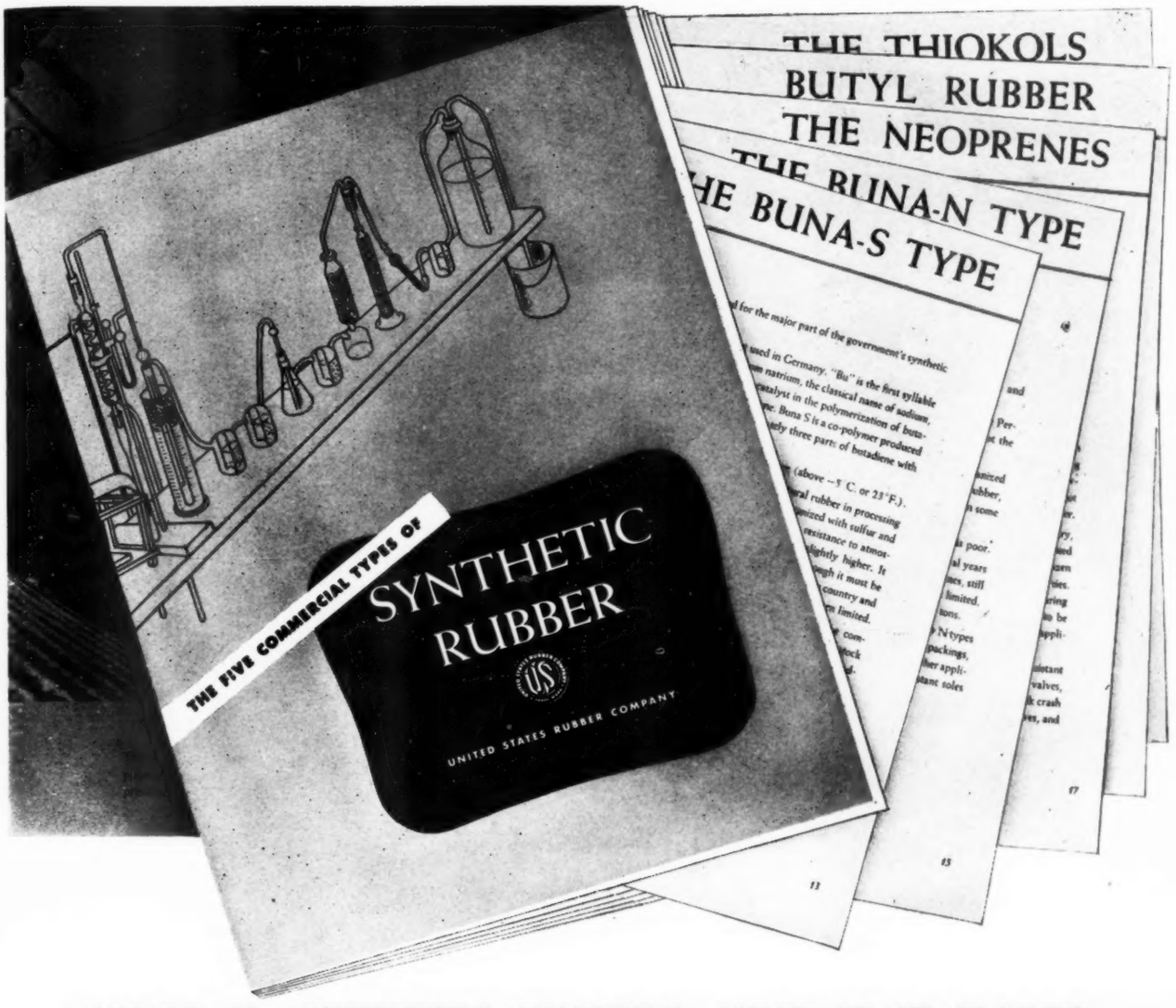
Chemical treatment

1. If rate of mud loss is low, allow viscosity to increase slightly, but keep gel strength low.
2. In more severe cases, use mechanical plastering agents such as cellophane, mica flakes, etc.
3. If cavity, usually necessary to set pipe before normal drilling operations are resumed.

High-temperature decomposition of phosphates

"Symptoms"

1. Temperature at flow line, 120°F. or higher.
2. Viscosity of mud high despite continuous additions of phosphates.



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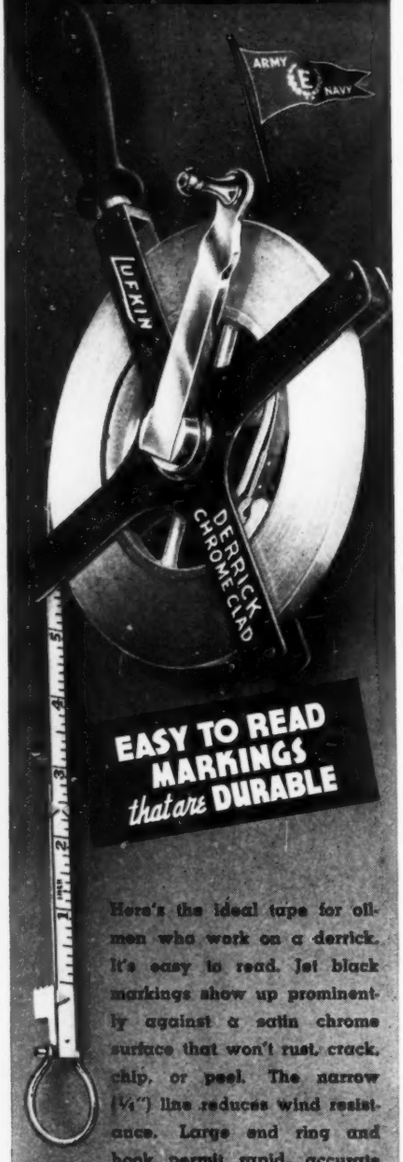

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Chemical treatment

1. Use Quebracho in equal proportion with phosphate.
2. If above not successful, use dicyandiamide. To be added rapidly to a concentration of 0.5 lb. per bbl. of mud, followed by addition of a mixture of dicyandiamide with complex phosphate or Quebracho as required to maintain satisfactory viscosity.
3. Excessive use of this compound sometimes produces objectionable reduction in gel strength of mud.

High concentration of colloidal matter

"Symptoms"

1. Viscosity high, and not improved by chemical treatment.
2. *Low water loss.*
3. Usually high total-solids content.

Chemical treatment

1. Reduce mud pH to less than 8.0, but not less than 7.2, by use of monosodium phosphate or sodium acid pyrophosphate. Watch gel strength of mud in reducing pH, as it tends to become too low to support weighting material and cuttings.
2. Alternate the use of the various chemicals available for viscosity control.
3. Dilute with water and maintain weight by addition of weighting material, if necessary.

Common chemicals in use for viscosity control

(Compliments of Arthur G. Levy)

The following list of chemicals in use for viscosity control of drilling muds is arranged in order of pH values, varying from a low of 1.5 to a high of 12.6—depending somewhat upon concentration:

Chemical	*Formula*	*Approximate pH*
Phosphoric acid	H_3PO_4	1.5
Gallic acid	$C_7H_6O_5$	3.4
Sodium acid pyrophosphate	$Na_2H_2P_2O_7$	4.8
Crude tannic acid	$C_{14}H_{10}O_9$	5.0
Chestnut extract	$C_{14}H_{10}O_9$ (approximate)	6.4
Sodium hexametaphosphate	$(NaPO_3)_6$	7.0
Sodium bicarbonate	$NaHCO_3$	8.2
Disodium phosphate	Na_2HPO_4	8.6
Sodium tetraphosphate	$Na_2P_4O_{13}$	8.7
Borax	$Na_2B_4O_7$	9.1
Tetrasodium pyrophosphate	$Na_2P_4O_7$	9.9
A mixed soda	$Na_2CO_3.NaHCO_3$	10.1
Soda ash	Na_2CO_3	11.0
Trisodium phosphate	Na_3PO_4	11.3
Sodium metasilicate	Na_2SiO_3	11.6
Caustic soda	NaOH	12.6

Many of the foregoing chemicals are marketed under trade or proprietary names, either in the pure state or together with small additives, which slightly change the formula or the pH, or both. These changes are usually of small importance, and have little or no value in practical use.

The foregoing pH values are for the concentrations which are most common in oil-field use.

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Construction and Economic Significance of Direct-Current Rigs for Deep Drilling Operations*

By R. A. J. DAWSON

Office of Petroleum Administration for War

Introduction

THE actual mechanical technique of deep drilling has been given very little technical attention by the oil industry. Even though the Gulf Coast region is definitely "drilling minded" there is as yet little recognition of the obvious fact that the Gulf Coast is at present in the initial stages of what will prove to be the most extensive deep-drilling campaign ever undertaken by the industry.

Three of the factors that will inevitably bring about deeper penetrations in this region should be mentioned in order better to evaluate the need for improved drilling techniques.

1. Thickness of the Miocene and Oligocene sections that geologists will ultimately desire to have penetrated. Coastal wells today are being carried steadily deeper, not with the desperation evident in other regions, but in the normal course of formational development.

2. Relative ease of penetration of coastal formations and consequent promise of economical operations.

3. Presence of a well-trained and interested, if not imaginative, drilling personnel in this area.

Purpose

The purpose of this paper is to emphasize the advantages of large d-c. full-electric drilling rigs for drilling to depths exceeding 11,000 ft. in economical competition with other types of drilling machinery.

Drilling Machinery

Integral oil-well drilling rigs may be divided into two general classes, those that are steam powered, and those deriving their original power from internal-combustion engines. The generic term "power-rig" is usually applied to all rigs other than those powered by steam.

"Power drilling," in the usual sense, means drilling performed by the use of internal-combustion prime movers, and the term "power drive" refers to the mechanism that accomplishes the power transfer.

"Direct-drive" power rigs are those that use internal-combustion engines or other prime movers to drive the drilling machinery through either mechanical or fluid transmissions.

"Electric rigs" have both electrical generators and electrical motive equipment effecting the power transfer between the original prime movers and the drilling machinery. Both internal-combustion engines and "high line" a-c. electric motors have been used successfully as prime movers for d-c. "electric rigs." As this paper is concerned only with integral rigs the use of a-c. prime movers will not be detailed.

History and Discussion

The regrettable scarcity of information concerning deep power drilling has handicapped the development of this type of operation. In technical publications to date no attempts have been made to define the operational spheres and depth ranges of the various types of power drives.

It appears that portable internal-combustion direct-drive drilling rigs have forecast the doom of steam rigs down to 5000 ft., except in instances of predictable work favorable to steam. This is due not only to the multiple field advantages of the small portable direct-drive rigs, but also because such rigs have an initial cost comparable to that of steam for the same depth range.

In the depth range from 5,000 to 11,000 ft. only an accurate analysis of predictable work justifies the purchase of equipment types. At the present time, fuel cost seems to be the most dominant factor over flexibility, portability, water cost, etc. In proved field use the gas-fired steam rig is still preferable, but in isolated areas steam is steadily giving way to power.

The overall operating efficiency of steam drive has not as yet been obtained with any type of power drive, and all attempts to design power rigs for deep drilling should strive to equal steam rig ease of operation.

Operating flexibility is not needed to any great degree in shallower drilling, which fact has enabled the small direct-drive rigs to replace easily steam rigs. The popularity of power rigs is due strictly to their overall economy and not to superior drilling ability, for steam power still remains the faster drilling medium.

There are at present two systems of electric drilling being used, the a-c. installations being outnumbered by the d-c. rigs as far as the heavier rigs are concerned. The a-c. rigs have proved their ability to drill deep wells, and have done so with equipment not designed for such heavy duty. Because of inherent characteristics, this system does not have the flexibility, overall economy, or potentialities of the d-c. method. This paper is concerned with the usage of d-c. machinery because it has already proved itself to be an unusually efficient and economical power medium.

Electric rigs can compete with other rigs in shallow areas only in certain instances, and their comparative cost prevents their wide adoption for shallow-to-medium depth wells. Naturally a major company could be assured of enough future specific locations so that it could make the most economical choice of power, but the same assurance is seldom found among the smaller operators and the contractors.

It is very important that d-c. power be fully understood before attempting to fit it into drilling schedules from 5,000 to 11,000 ft. There is always the possibility that future improvements of direct drives may enable them to replace other types of power transmission down to 11,000 ft., but beneath that depth, electric power affords a load distribution more inherently advantageous than other power drives.

In the course of years of detailed work that led to the writing of this paper the opportunity was taken to either work upon or to analyze the field performance of almost all of the large power rigs in Coastal Texas and Louisiana, including many direct-drive rigs along with all known large electric rigs owned by major companies, independent operators, and drilling contractors.

There is a distinct prejudice against electric power by field men and engineers in many quarters; however, from long and detailed field comparisons of electric rigs to others, many instances of proved economy in deep drilling can be recorded. The usual case history of the d-c. rig is that soon after delivery it was called upon to perform tasks all out of reason with respect to its designed rating. Electric rigs, properly designed, have a great reserve capacity for their tailor-made work, but a small electric machine is never sympathetic to overloading.

*Presented before Southwestern District American Petroleum Institute Division of Production, Houston, Texas, April 29 and 30, 1943.

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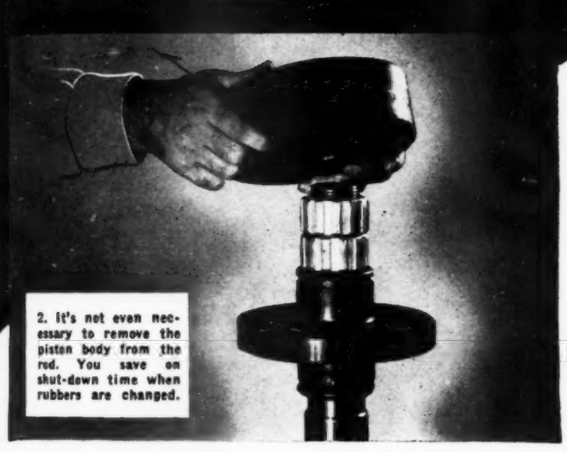

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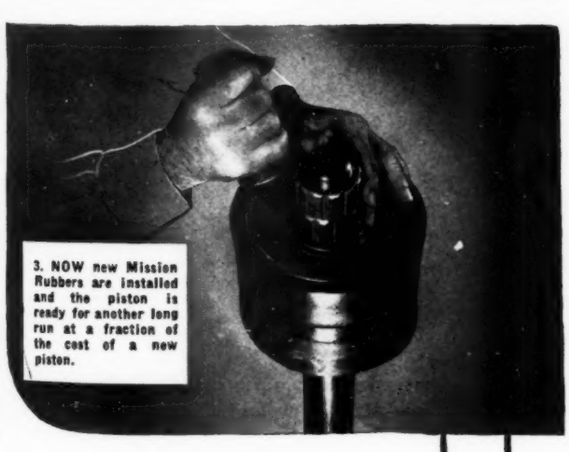

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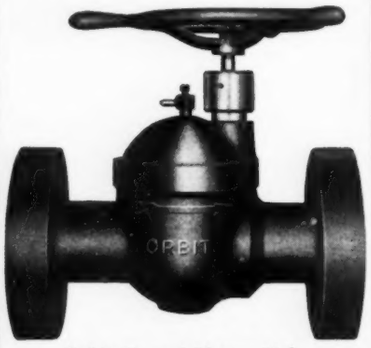

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Although most seem unaware of the fact, much of the bad reputation of electric rigs is due to misunderstanding between the so-called "practical men" and technicians of the drilling firms, the supply companies, and the electrical manufacturers. As a well known illustration, an electrical manufacturer designed an electrical setup for 10,000-ft. drilling, only to have the supply company add a bigger drawworks and sell the rig for 12,000-ft. competitive drilling. Before reaching 10,000 ft. it was necessary to add a third prime mover engine, and because of unavoidable inflexibility due to hybrid design, deeper operations are conducted only with great difficulty.

Few large electric rigs have been designed and constructed so that the final products were satisfactory from both an electrical and field performance standpoint. The proper design of a full-electric rig is realized when the flexibility requirements of the practical field men are fully satisfied through the application of economical mechanical and electrical engineering.

In designing complicated and synchronized direct current rigs, one must be very sure to use only the best of available equipment, and the attempts of any one supply house or electrical manufacturer to engineer the assembly must be completely nullified. It has long been standard practice for supply companies with related distribution connections to encourage usage of associated equipment inferior to that of other manufacturers, and due to the lack of "practical engineering," this has resulted in costly mistakes.

Some "hybrid" rigs have been built on various semi-electric principles, but all such designs have the common disadvantages of direct-drive power rigs, inflexibility and bulky design. A full-electric rig can be made to have essentially the same layout as a steam rig, and this fact is important in many areas. Layout and arrangement can be made to follow conventional setup patterns on piling, barges, and upon marsh mats. In all cases in which deep drilling of more than 11,000 ft. has been attempted, enough performance difference has been demonstrated with the semi-electric rigs to justify full electrification. Many operators avoid electrical rigs because of the transportation difficulties involved with the heavy machinery, and others hesitate to make such a large initial investment in what they consider an unproved drilling technique.

Direct-Drive Power Rig Trends

During the last six years tremendous development has taken place in many types of direct-drive, and clutches and couplings are still undergoing continuous improvement. Smoothness has been greatly increased by slowly feeding friction clutches, hydraulic clutches, air controls, etc., and hydraulic transmissions have certainly not reached their maximum possible efficiency.

At the present time no means of direct-drive gives promise of having the necessary characteristics to handle the enormous loads imposed upon equipment in drilling below 11,000 ft. in competition with steam power. It is also doubtful that the necessary hairline power distribution can be had in the near future with direct-drive unless the price of the mechanical equipment skyrockets.

Large direct-drive rigs being designed today have a cost comparable to that of electric rigs but still lack the flexibility so necessary in deep operations. A recent trend in the construction of direct-drive rigs is to place the prime movers behind the drawworks and to drive the pumps off the same transmission that drives the drawworks.

The complexity of direct-drive hoisting machinery has reached the point where the drawworks and transmission unit alone costs over $55,000, more than twice the cost of a 10-in. unit either for electric or steam drive. Even with more complicated speed reduction than is practiced today on direct-drive rigs it will not be possible to approach the overall efficiency of both slush pumps and drawworks that is easily accomplished with electric drive.

Attention should be called to the fact that if heavy drill strings are to be hoisted, at least 1000-hp. must be concentrated behind the drawworks on direct-drive designs. Although this concentration of power may effect some sort of drawworks drive, simultaneous operation of heavy slush pumps will be undeniably related to both the power and speed demands of the drawworks.

The location of several large engines behind the drawworks not only poises great alignment, movement, maintenance, control, and fire hazard problems, but also dictates rig layout and derrick substructure height to a very restrictive degree. Only by the addition of large, costly fluid transmissions will pumping equipment on direct-drive rigs ever realize the creeping speeds easily obtainable with direct current motor drive.

D-C. Rigs

The fact that steam equipment is naturally flexible has tended to obscure the fact that electric equipment must be especially matched to its most optimum type of work.

Only during the last several years have full electric rigs been designed and

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constructed to handle easily the loads necessary below 11,000 ft. in competitive drilling under all circumstances, and the performance of these larger rigs can be best judged by a few statistics.

On a water location 16 miles from the supply dock, a full electric d-c rig made 12,913 ft. of hole in only 60 drilling days. This depth was made with 4½-in., 16.60-lb. drill pipe, which was pulled on the last trip in the fast time of 3 hours and 55 minutes, with no especial attempt being made to shorten pulling time.

It is interesting to note that the above time was made with a seven-year old, three-shaft, four-speed, "eight-inch," drawworks that was not even oil-bathed. With an improved hoisting setup, even better time would have been made, but 14,000 ft. of 4½-in. drill pipe could have been handled with this unit provided that its lubrication system had been improved and the proper hoisting speeds maintained.

Given sufficient design, prime mover horsepower, and electric power, d-c rigs can compete economically with steam to depths of 15,000 ft., provided these rigs be accorded proper maintenance and well supervision.

Thus far, only four drilling rigs using d-c. electric power have been built that could easily compete economically with steam rigs to depths beyond 11,000 ft., but the performance of these rigs has plainly indicated the many advantages of electric power for the deep wildcats of the future.

In casing future wells to 15,000 ft., hook loads of 450,000 lb. will be imposed, and high starting torques will be necessary to handle such loads. Such torques are supplied today by d-c. electric motors, and it is thus hard to account for the trend toward direct-drive, which fails to recognize this established fact. If future torque converters are to handle slow speed, high-torque loads they must transmit the power between the faster and slower machinery by slippage through hydraulic media, which slippage itself is usually synonymous with heat and loss of power. We are fortunate that there is enough slack in drilling tool strings so that direct-drive rigs are very satisfactory at medium depths, but the power transfer must take place much more smoothly and efficiently at extreme depths.

Advantages of full electric d-c. rigs over direct-drive rigs:

1. Complete lack of interdependence of drilling and pumping operations.
2. Smoothness of hoisting operations regardless of load.
3. Greater torque capacity for heavy loads at slow speeds.
4. Eliminate torque converters and clutches.
5. Predictable maximum safe load throughout prime movers, electrical and drilling equipment.
6. Wider range of speed and torque characteristics imparted to power pumps.
7. Ability to stall driving electric motors without stalling or altering the speed of prime mover engines.
8. Ease of maintenance of balanced power plant running at constant rated speed.
9. Ease of assembly due to mobility and flexible connections.
10. Power plant and pump layout can be altered to suit changing conditions.
11. Greater ability to absorb shock loads.
12. Greater ability to use V-belted transmissions for prime movers.
13. Easier to change type of prime movers to meet fuel changes.
14. Safer location of remote power plant in gaseous atmospheres.
15. Derrick floor height not restricted.
16. More electrical accessories.
17. Speed and torque of all units always accurately indicated.
18. Smoother separate electric motor driven rotary.
19. Shorter rig-up time.

Disadvantages as compared to direct-drive rigs:

1. General complexity and need of more attention.
2. Heavier and additional units to move.
3. Need of more intelligent personnel.

Advantages and disadvantages of d-c. and steam rigs:

A. *Advantages*

1. Fuel cost (average on 11,000 plus depths).
   Electric rigs
   - Diesel—$35.00 per day fuel and oils.
   - Butane—$140.00 per day fuel and oils.
   - Gasoline—$155.00 per day fuel and oils.
   - Gas—$4.00 to $12.00 for 90,000 cu. ft. daily, plus oil, etc.

   Steam rigs of equal size
   - Fuel oil—$260.00 per day.
   - Gas—$60.00 to $180.00 per day for 1,200,000 cu. ft. per day.

2. Water cost
   Electric
   - Average about 150 bbl. day, seldom over 500 bbl. per day with use of waste water washdown pump.

   Steam
   - Use about 600 to 800 bbl. per day makeup water with condensers.
   - Without condensers use from 2000 to 3500 bbl. per day.

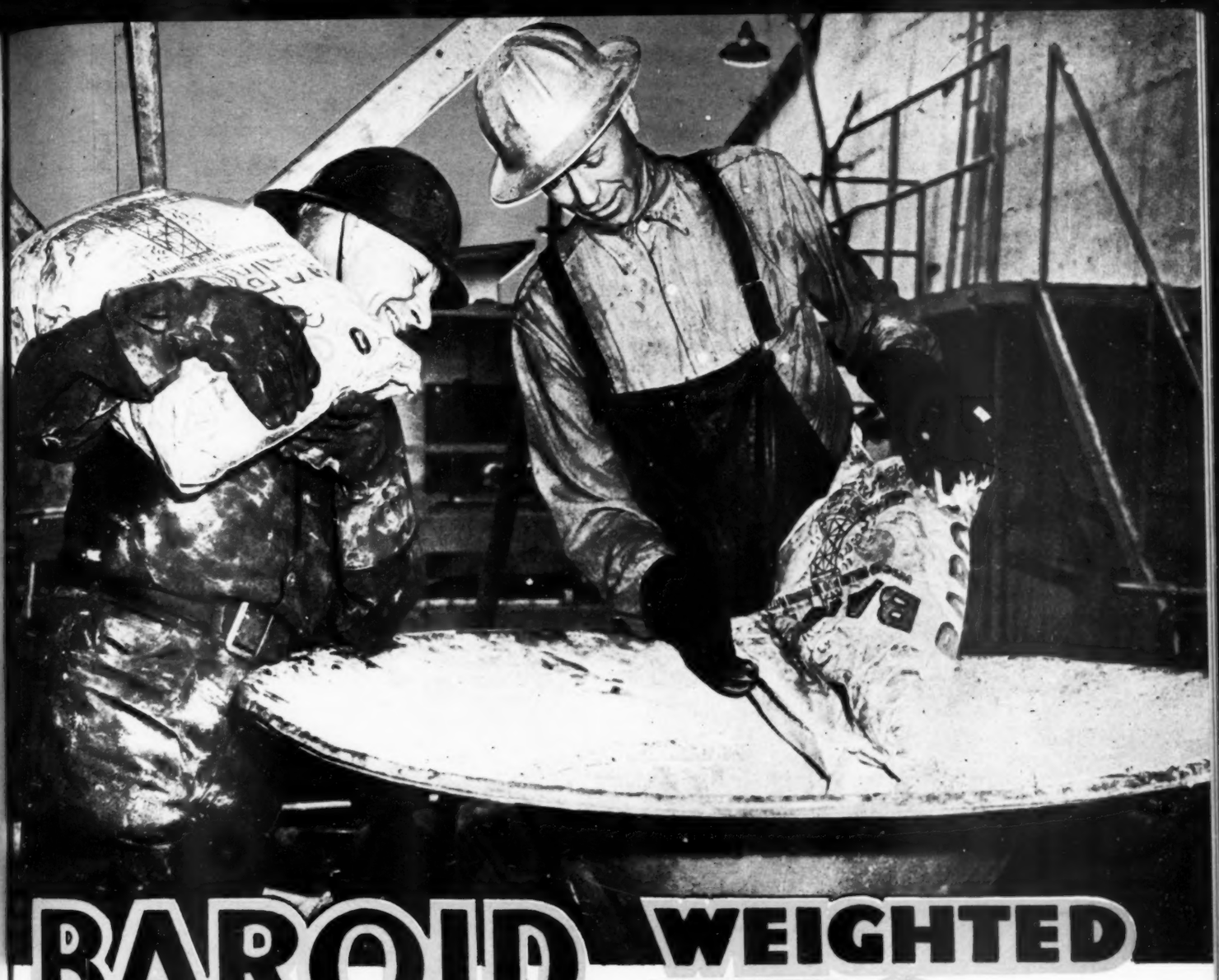
3. No steam lines or remotely controlled water supply.
4. Speed and torque of all units always accurately indicated.
5. Less vibration of hoisting units.
6. More electric and flexible accessories.
7. Smoother and faster drawworks clutching.
8. Driller has centralized control of all operations.
9. Less fuel oil haulage or barging.
10. General water supply problem less costly.
11. Motorman able to do floorwork much more safely than fireman, because of synchronized power plant.

B. *Disadvantages*

1. High initial cost.
2. General complexity and need of more attention.
3. Need of more intelligent field men.
4. Need of field technical and engineering help.
5. More units to move.
6. Extreme heaviness of pumps. (For large rigs.)
7. Slightly longer rig-up time. (For large rigs.)
8. Slightly higher maintenance cost.
9. Inertia action of power pumps. (Have all speed and power variations, but are not as flexible as steam pumps during cementing, squeezing, fishing, sidetracking, stuck pipe, fishing jobs and other quick power variation demands.)
10. Inertia action of rotary. (This factor can be eliminated by electrical control of proper sort.)

Marine Operations

Electrical rigs are especially adaptable to the deep tests drilled in the marshes and shallow bays of the Gulf Coast. Most of the marine electric rigs to date have used separate power barges, but it would easily be possible to incorporate a complete electric rig on one twin-hull, 56-ft. by 150-ft. drilling barge. The power plant could be installed on the upper level directly behind the drawworks where it may be easily controlled and maintained. There should be careful protection against fire hazards if this type of construction is used, and it is partly due to the danger of fire that small, separate power barges have been designed. Power barges are usually moored alongside the larger drilling barges, and can be quickly detached and floated away in case of well blowout or fire. Such barges usually contain only the power plant and controls and are usually about 35 ft. wide and not over 60 or 70 ft. long. If separate floating power barges are to be used in open waters they should be as large as



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BAROID, the *pioneer* weighting material for drilling mud, has been successfully used in thousands of wells to control formation pressures and to prevent caving. Muds suitably weighted prevent blowouts. The speed of drilling operations is also increased. BAROID has a high specific gravity (almost twice that of most native clays) and will make pumpable muds weighing as much as 20 pounds per gallon (150 pounds per cubic foot). It may be added to the mud by means of a cone-and-jet type mixer, as shown above. BAROID is easy to transport and will not deteriorate in storage. BAROID is immediately available in 409 locations in the United States and Canada.

BAROID SAVES VALUABLE CASING

BAROID weighted muds have made possible the saving of thousands of tons of casing. Previously used protective strings can often be eliminated by sufficiently increasing the mud weight with BAROID to hold back caving or sloughing formations and high gas, oil and water pressures.

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economically possible, as in rough weather they would be easier to manage. Most of the boiler barges constructed to pair with drilling barges on open water location are of the submersible type.

If drilling is to be done on piling, or on marsh mats alongside bayous or canals, the power barges may carry the mud tanks, pumps, water pumps, shale shakers, and accessories, in addition to the power plant. Temporarily efficient and economical setups such as this may be used in quiet waters, all of the equipment being secured to the deck of an ordinary barge.

Although barges of this type are not considered stable enough for rough open water operations, a unit of this type has drilled the second deepest open water test, which went to nearly 13,000 ft. In arranging a barge of this type, the power plant placed on one end will balance the heavy mud pumps on the opposite end, the mud tanks occupy the center of the barge. With this setup the barge maintains an even keel, regardless of the amount of weight of the mud. A complete 1000-hp. plant, two 20-in. stroke pumps totaling over 150,000 lb., and two large tanks of heavy mud have been installed on the deck of the barge of 30 ft. by 98 ft. dimensions.

Horsepower Requirements

In referring to comparative performance and construction, it is necessary to fix some total depth to which both electric and steam rigs are to penetrate. In this paper the discussion of all future design and construction is to be based on units capable of competitive drilling to 13,000 ft. with 4½-in. drill pipe and to 15,000 ft. with 3½-in. drill pipe.

To drill to the above depths an electric rig should have at least 1000-hp. as far as the b. hp. ratings of its prime movers are concerned. This amount should be available, and is the minimum necessary even if full mechanical and electrical flexibility is obtained.

If electrical drilling is to be done shallower than 11,000 ft., it should be understood that large power rigs are very heavy, and that ones of this size require about 720 man-hours (15 men working four 12-hour days) in moving from a stacked position to full readiness to drill rathole.

This time assumes a land move onto ready-built derrick of high substructure, with the pump and power plant board mats being already constructed, and is the fastest possible time with all needed traction help.

It is possible to set up a comparative steam rig in about 320 man-hours (15 men working two 12-hour days) under similar circumstances, the units being lighter, and in some respects more easily assembled.

Prime Mover Engines

Regardless of what type of power is used the load should always be divided equally between the prime mover engines, which should be at least three in number, each being of from 330 to 500 b. hp. With triple units of this kind sufficient power is available to drill with two engines, and the drill pipe may be withdrawn from the hole by a single engine if the well is not deeper than 11,000 ft.

Available oil-field engines range in speed from 400 to 1200 r.p.m., with their weights being in approximately inverse ratio. As portability and dependability are both of extreme importance, much thought of future locations should be exercised before selection of type is made. Barge setups are well designed with the simpler, heavy, slow-speed engines, but portability needed for land operations has encouraged the use of the lighter, high-speed machines.

Diesel engines of modified pressure scavenging 2-cycle design are now being used for military marine service, giving about 500 hp. at around 1200 r.p.m. These engines should be ideal for direct connective use plants because of their high horsepower output per pound of weight. They are constructed by a well known automobile manufacturer, and should, along with other recently designed high speed diesels, revolutionize oil-field power plants.

Direct-connected generative plants have been used for some time with shallow drilling rigs and the new high-speed Diesels will provide sufficient power to do deep drilling. It will be possible to use the accurate construction facilities of the large factories in assembling these large in-line plants, giving units of better bearing and shafting alignment. Moving and rig-up time should be greatly reduced, and the overall efficiency of the power plants greatly increased.

It will be much harder for a clutch connected direct-drive power rig to use high-speed engines than it will be for a full-electric, d-c rig to follow the high-speed trend. Clutching troubles will naturally increase at high speed, and it is impossible to obtain full engine power unless the motors are up to rated speed. Until torque converters and hydraulic transmissions are made much larger and more efficient, direct-drive rigs will not have the necessary smooth power conversion to do competitive deep drilling.

Transmissions

For purposes of load division, balancing, and speed kickup, the V-belt type has proved much better than chain or gear transmissions for drilling operations of the heavy class considered.

Among the important reasons for the efficiency of V-belt transmissions are the following:

1. Positive load design and length of belts.
2. Different spacings possible according to belts used.
3. Low upkeep cost.
4. Long life of large V-belts.
5. Very effective load distribution.
6. Absorption of shock loads and thrusts.
7. Ease of construction of transmission.
8. Ease of repair and maintenance.
9. Visibility of system.
10. Simplicity and low initial cost.
11. Ease of lubrication.
12. Lightness and unitization with motors.
13. Correction of small misalignments without harm.
14. Quickly rigged up and torn down.

In some early electric rigs the prime movers were not used in unison through transmissions, and loads above the rating of one prime mover were handled by compounding the electrical equipment, at times in series, and at other times, in parallel. This type of operation not only needed more complicated electrical control, but also prevented rapid equal distribution of load to the prime movers.

Still another type of early assembly consisted of many small gasoline or Diesel engines directly connected to small generative units, being constructed only with much expenditure of costly equipment, and resulting in unavoidable complexity and efficiency loss. This type of design cannot possibly handle the high voltages and heavy amperages needed in drilling to extreme depths because the electric equipment is not large enough to handle the necessary burden.

In constructing any type of electric rig, regardless of size, internal-combustion engines of at least 175-hp. or over should be used, as only engines of this size are sturdy enough to provide dependable power and stand up under the treatment that must be given to all oil field equipment.

Generating Equipment

In like fashion the generative units should be large enough so that each may accomplish its appointed task without any aid from any of the other electrical equipment of like size. Semi-enclosed types are favored and are rated 40-

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POWER TO WIN means striking power — and power available at instant notice, even under the guns of the enemy, to keep our hard-hitting equipment on the move and in action. Absolute dependability, the greatest asset of Continental Red Seal Engines, is providing POWER TO WIN for vital equipment on all fronts — in the air, on land and sea; also for our farms, oil fields, and for industry.
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60°C. rise to provide an adequate safety margin for overloads and high ambient temperatures.

We are fortunate that electrical equipment of the power output and rotative speed most suitable to our use is of a size that is readily transportable. Generators may be had up to 500-kw. that weigh less than 15,000 lb., and can be easily handled in twin units by medium winch trucks.

Power of the 300-400 v., 1200 r.p.m. generating equipment used in the oil fields has ranged from 150 to 500-kw. and this equipment has in most instances been but slightly modified from the general industrial equipment of like nature. The generator field controls are for the most part adaptations of similar controls used in mining, crushing, hoisting and like operations that demand wide variation in speed and power. Of the three electrical manufacturers supplying large electrical drilling equipment two favor 1200-r.p.m. generators whereas the other provides 600-r.p.m. machines.

As weight is such an important transportation factor the 1200-r.p.m. machines have a very definite advantage because pound for pound they are capable of higher power output. Standard 600-r.p.m. oil-field machines are rated around 200-250 kw. and are not large enough to handle the extreme loads of deep drilling without complex compounding.

The voltage of available generators and motors ranges from 200 to 400 volts, being limited at the higher figure because of protective insulation design. Established industrial insulation standards limit maximum voltage of such units to 600 volts, but oil-field conditions preclude use of such high voltages. Some of the lower voltage machines were used for series compounding, giving good speed characteristics, but resulting in lack of torque flexibility. Compounding has been found not only to be a needless operation, but by its inherent nature places restrictions either on voltage or current flexibility, and hence upon speed or torque.

Voltage and Amperage

Because of the wide variance in both speed and torque demands, generators of 350 to 400 voltage at 1200 r.p.m., and amperages up to 800 to 1000 at full load, have proved best for heavy-duty drilling rigs. Most of the rigs built for 350-v. operation are designed so that they slightly overrun this voltage figure at high-speed, light-load performance.

At least three generators, totaling nearly 1000 kw. are needed for this extreme deep service, and if possible a fourth generator increasing the power to 1200 kw. should be procured. A three-generator rig must have at least 1000 kw. if it is to do deep-well hoisting, and in rigs of this size, units can be best divided into units of 500, 350, and 175 kw.

If four generators are to be used the following distribution would be found desirable, 500 kw. (hoisting on trips, hole pump while drilling), 330 kw., and two 175 kw. It is possible to withdraw up to 14,000 ft. of 4½-in. drill pipe with a 330-kw. machine, provided the drawworks motor is of sufficient size, but a 500-kw. machine would be much better for steady deep service.

Electric motors are limited in power only as they are limited in their capacity to stand heating, a large electric motor being able to stand very heavy armature current overloads, provided that these currents are not maintained too long. The heat generated must be dissipated, and as this heat is the product of the square of the armature current times the resistance, the current that the motors are able to bear is the limiting factor in the design of the circuit.

The torque of a d-c. motor is almost proportional to the armature current, and the fundamental design of the rig must be built around the ultimate torque that the electric motors will have to deliver.

The power output, or time rate of doing work, is the product of the voltage times the amperage; hence, inasmuch as the voltage is directly proportional to speed, the need of high voltage generators to get sufficient speed into the motor (when possible) is easily seen.

Generator Controls

All generators and exciters rotate constantly at 1200 r.p.m., or other rated speed, the generators (and hence the motors they pair with) are controlled by use of a type of Ward-Leonard oil-immersed generator field control.

This control consists essentially in using the voltage of a small 25-kw. exciter generator to vary the field current in the larger generator. A large electric rig should have at least two exciter generators of 25 or more kilowatts, these small machines turning at 1200 r.p.m. with the remainder of the rotating generative equipment, and *constantly* putting out 125 volts. These small exciters have a permanently charged field magnet construction, and by means of adjustable throttle resistances these small generators are used to control the large generators and hence the large motors.

The armatures of the large generators and of the large driving motors are simply a closed circuit of heavy copper cables, and the driller controls each individual driving motor by means of the small wire circuit of the generator field. These driving motors can be reversed easily by reversing the field current of the generators, which changes the polarity and flow of the armature current.

General Design Advantages

The main advantages of the general design as set out are as follows:

1. Equal load distribution between prime movers.
2. Ability to continue operations with units shut down.
3. Sufficient prime mover horsepower concentrated in one plant.
4. Rapid assembly of power plant and available power.
5. Constant prime mover and generator speed.
6. Ease of maintenance at rated speed operations.
7. Instantaneous response to load demands.
8. Capacity to withstand shock loads.
9. Flexibility of armature circuits.
10. Full floor control of speed and torque of units.

Ward-Leonard Control

As stated before, it is not possible to have the same degree of automatic electrical control on drilling equipment that is found advantageous in installations where the controls can be better protected and permanently installed.

The Ward-Leonard is essentially a simple rheostatic control of generator field with provision being made for starting, reversing, and stopping of this field, in order that the driving motors may also perform these operations.

Starting and reversing features are usually imparted by one of two methods:

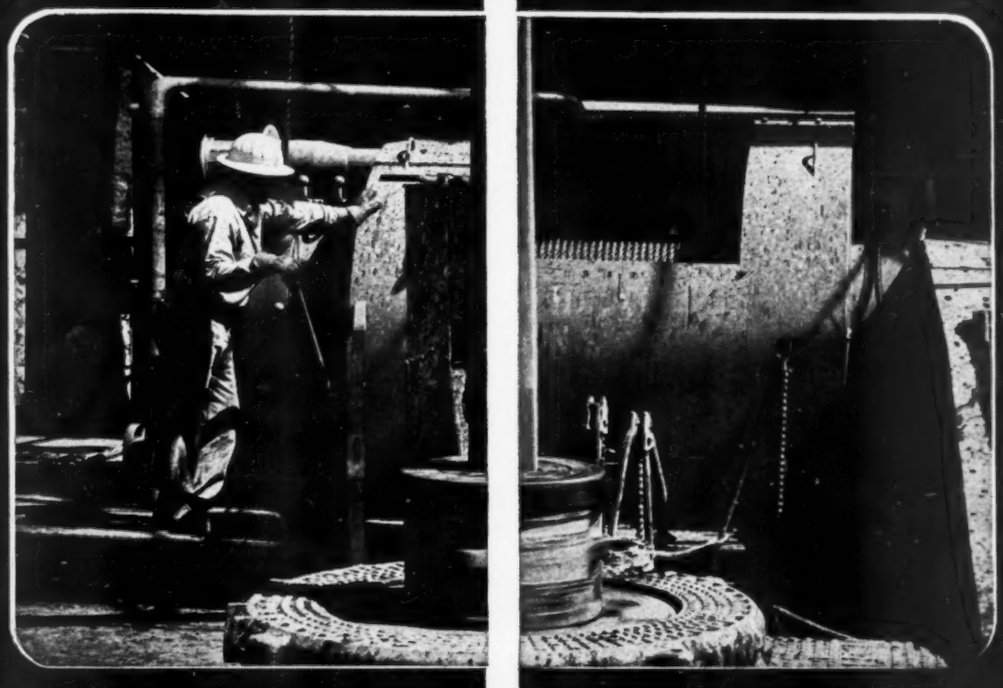
1. Location of starting and reversing mechanism within the driller's floor control rheostat.
2. Location of the above mechanism in the power plant exciter control cabinets.

Pumping Equipment

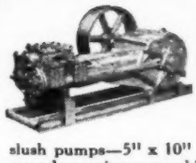
In order to maintain mud pressures of 1200 to 1700 lb. per sq. in. and provide sufficient volume, it is necessary to use heavy-duty 20-in. stroke power pumps. At the present time there are two widely used makes for this type of service, both taking liners up to 7¾ in. in size. On 13,000-ft. wells, these large pumps have given very good service, handling working pressures up to 1700 lb. per sq. in. with 5½-in. liners, at 40 strokes per minute.

The extreme heavy weight of large power pumps is as yet an unsolved bad

NATIONAL SLUSH PUMPS KEEP THINGS MOVING...

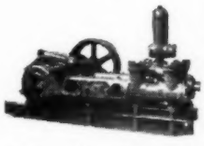


Down where it counts the most!



THE IDEAL TYPE D-50

Designed for slush service on shallow rotary and seismograph rigs—has operating convenience and dependability of larger slush pumps—5" x 10" bore and stroke—1000 pounds maximum working pressure—50 maximum rated hydraulic horsepower at 60 r.p.m.



THE IDEAL TYPE C-150

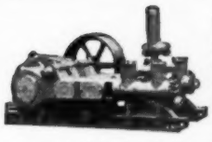
For portable and semi-portable rigs and semi-shallow drilling—6¼" x 12" bore and stroke—2000 pounds maximum working pressure—150 maximum rated hydraulic horsepower at 65 r.p.m.—Due to higher operating speeds will deliver a greater amount of fluid at higher pressures and less hose whip.

THE IDEAL TYPE C-350

For the deepest regular drilling—7¾" x 18" bore and stroke—3000 pounds maximum working pressure—350 pounds maximum rated hydraulic horsepower at 55 r.p.m.—power and pressure ratings allow duplication of corresponding size steam pump performance.

THE IDEAL TYPE C-100

The continued extension of rotary drilling into the shallower fields and the trend to reduced diameter holes have created a demand for a smaller power driven slush pump with the same relative drilling efficiency as the larger deep hole types. The Ideal Type C-100 Power Driven Slush Pump is especially made for these requirements. It has the same general design as the larger Ideal Type C Power Driven Slush Pumps—10" x 5¼" bore and stroke—1500 pounds maximum working pressure—100 maximum rated hydraulic horsepower at 65 r.p.m.



THE IDEAL TYPE C-250

For ordinary deep drilling requirements —7¼" x 15" bore and stroke—2500 pounds maximum working pressure—250 maximum rated hydraulic horsepower at 60 r.p.m.—Adaptable to all types prime movers—shorter, more portable with no sacrifice in volume and pressures.

Model No.	Max. Liner Size	Stroke	Max. Working Pressure	Pressure Rating of Full Size Liner	Rated Speed	Rated H. P.	Weight Pounds
D-50	5"	10	1,000	450	60	50	5,725
C-100	6¼"	10	1,500	520	65	100	12,250
C-150	6¼"	12	2,000	550	65	150	17,000
C-250	7¼"	15	2,500	710	60	250	28,975
C-350	7¾"	18	3,000	800	55	350	36,400

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feature of such pump design. Used with a 400-600-hp. electric driving motor, the 53,500-lb. pump with all accessories weighs over 75,000 lb. The electric motors weigh around 11,000 or 12,000 lb., and must be mounted on adjustable mountings on the extensions of the 14-in. by 14-in. I-beam pump skids. It is not possible to handle a single unit of 75,000 lb. easily even with our present large tandem trucks, and the motors must be removed from the base extension during rig moves.

Pumps of 20-in. size are run in surface hole up to 54 to 56 strokes per minute with 7¾-in. liners and supply sufficient fluid to make very fast hole. Throttle controls for the hole pump, the stirring pump, drawworks, rotary, etc., are all mounted at the driller's position and he has complete control of the speed and power of all units. Much has been heard to the effect that power pumps will not make hole, but this is not true of well-primed power pumps of modern design.

Large electric-drive power pumps are not as flexible as steam pumps of comparable size, but the degree of flexibility is much greater than that which is obtained with direct-drive pumps. Relief valves must be used to prevent damage to water end castings and to safeguard personnel when abrupt stoppages of circulation result. Because of the powerful electric motors used, it is possible to run a unit of this sort at very slow speeds, and such units may be stalled for long periods without damage. Direct-drive power pumps cannot be stalled without engine stalling and the greater flexibility of electric drive is much better adapted to pumping down cement plugs and similar operations, where shearing of relief valves is best avoided.

AMERICAN RADIAL ROLLER BEARINGS are *precision built* for almost every heavy-duty bearing application where the load is radial. Use of AMERICANS in heavy machinery, lowers maintenance costs and increases the performance-life of vital equipment. AMERICAN RADIAL ROLLER BEARINGS are readily adaptable because the outer race is removable for easy assembly. Rugged durability and long-life are assured by special heat-treated alloy steel. Constant inspection and precision tests make for absolute accuracy and smooth, quiet performance. AMERICAN RADIAL ROLLER BEARINGS are made in five styles, 4 S.A.E. series and 85 sizes. Special designs to your requirements are also available. Write today.

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AMERICAN
Heavy-Duty ROLLER BEARINGS

Drawworks

Drawworks should be driven by a 350-volt, 1000-r.p.m. motor of at least 400-600 hp. through a reduction gear of about 2.25 or 3.0 to 1 ratio. The exact reduction depends to a large degree upon the sprocket ratios through the drawworks, but the motor should be turning its rated r.p.m. when the drilling line is being pulled at its normal high rate of travel. As most motors of this voltage or slightly higher are built to overrun slightly this figure without harmful results, a very fast and snappy unit action is obtained.

If operations are to be conducted below 13,000 ft. with 4½-in. drill pipe, two drawworks motors should be installed. These twinned motors should drive through a double reduction gear, and should be each of at least 300- to 400-volt rating. In case of failure of one unit the remaining motor will provide sufficient power to come out of the hole at very slow speed.

A policy of having motors of sufficient horsepower to absorb high current loads must be followed to insure successful operations, and although it is possible to overload a large electric motor to several times its rating, the additional cost per horsepower is so small that it is best to provide at least 600 hp. for 4½-in. drill pipe loads to 13,000 ft. and 800 total electrical horsepower for equivalent pipe loads below that depth.

Conventional steam engines of 12 in. by 12 in. and 14 in. by 14 in. size develop from 1400 to 2000 hp. at stalling torque with 400 lb. per sq. in. steam pressure. Because of this high rating some confusion results from the ability of a much smaller rated electric motor to do equivalent hoisting work. As stated before, given sufficient generative power, the torque obtained is limited only by the ability of the armature circuit to stand heating, and as the interval of high torque is relatively small, the motor does not have time to overheat.

Assume, for purposes of illustration, that the cycle time of withdrawing one

stand from off bottom at 13,000 ft. is 110 sec. Of this total time only about 65 sec. would be hoisting time and the lightly loaded motor has sufficient time to cool off during the remaining 45 sec.

The long strings of drill pipe are hard to start moving, because their tremendous inertia and friction must be overcome; however, readings of horsepower required to pull 13,000 ft. of 4½-in. drill pipe (16.60 lb. per ft.) with a modern electric drive drawworks show that with ten lines strung only about 950 hp. is needed to start this much pipe moving and 850 hp. will handle the moving string easily.

On pulling on stuck pipe the d-c electric motor is still very powerful and yet fully flexible. It is easy to pull any desired amount of strain and stall the motor, catch the strain on the brake, then slack off and repeat the operation indefinitely. If tremendous strains are to be taken, they may be gradually increased to the desired maximum as with steam, the strain then being maintained with the brake. There is never any need to hold high amperages on the electric motor for long periods of time, and it is easily possible to pull a 2500-amp. torque on a 400-hp. continuous duty motor without hurting the machine, as long as the current is not maintained too long. A torque of this type can exert upwards of 500,000 lb. upon the drilling string when used through a modern drawworks, and additional strain may be pulled with this rating motor.

Heavy pulls should be taken gradually, and if evenly increased, strains to the limit of the drilling line may be imposed. As it is not possible to overload or stall the engines, large electric rigs have tremendous pulling capacity. Horsepower is the *time rate of doing work* and the increments of power are transformed into mounting strain which can exceed the breaking strength of the drilling line.

Summary

In proportion to the amount of sales work involved, very little electrical equipment has been sold to the drilling industry as compared to other industries. For this reason, manufacturers have become discouraged with the reception that their field products have received, and have not emphasized electrical drilling equipment to any great degree during the last several years. This slacking of interest was apparent even before the electrical manufacturers became loaded with war orders, and was due to the fact that little interest was being shown by the oil industry in electric drilling.

Large electric rigs must definitely be tailor-made of the very best of available equipment, but they fit very well into drilling programs of certain types. There is no question of the many advantages of electric power in the drilling of deep, remote wildcats, and it is hoped that the oil industry will become increasingly cognizant of this economic oversight. An investment of $250,000 or thereabouts is without question a large sum, but such steady savings in operational cost are possible on the deep penetrations of today that the $50,000 difference between the price of electrical and steam equipment can be readily overcome.

The future of deep electric drilling depends upon the manufacturers' ability to establish the economy and flexibility of electric power, and to do this they must develop technical personnel that is thoroughly familiar with actual drilling procedure. Development of such personnel will take time but only by such a procedure will the oil industry capitalize on those simple flexible designs that are correlative to future economical deep operations. The natural tendency of manufacturers to over-design and compound should be modified because such complexity is not only needlessly expensive but is also much less dependable.

OPERATIONAL CYCLE TABLES

(Using 350 v. 330 kw. generator and 350 v. 400 hp. motor)

Hoisting from 13,000 ft. (total time—110 sec.)

Operation	Starting	Hoisting	Breaking out	Standing back	Falling block, etc.
Time, sec.	4	61	6	5	34
Generator, kw.	725	655	60	..	..
Motor, hp.	950	850	75	..	..

Running in 140th stand (time—60 sec.)

Operation	Hoisting (empty)	Stabbing and makeup	Pickup to free slips	Lowering pipe, etc.
Time, sec.	11	14	3	32
Generator, kw.	375	50	700	..
Motor, hp.	480	60	900	..

Acknowledgments

A great deal of the progress of the design of both mechanical and electrical rigs has been due to the active work of D. M. MacCargar, formerly with the Allis Chalmers Manufacturing Company, and now an independent consulting engineer of Houston, Texas. Much of both the history and electrical data that developed into this paper were learned either from or through association with MacCargar in constructing and operating d-c rigs.

It was through working with J. C. Morrison, of the Douglas Aircraft Corporation, formerly employed as electrical engineer for O. W. Dyer, Sr., and Jr., drilling contractors, that a good deal of the control and maintenance information was developed.

The author is deeply indebted to O. W. Dyer, Sr., and O. W. Dyer, Jr., for their interest and consideration during the time that he was in charge of their electrical drilling operations.

Finally, the author expresses his thanks to his superiors in the Office of Petroleum Administration for War for permission to present this paper, with the understanding that the paper represents the author's personal viewpoint and experience gained prior to joining the PAW, and does not constitute an official expression of opinion of the PAW.

EDITOR'S NOTE: Additional data have been compiled by the author on the subject discussed in this paper and will be published in a later issue of *The Petroleum Engineer.*

☆ ☆ ☆

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WISSCO PRODUCTS

A.P.I. Activities and Cooperation With the War Production Board in the Simplification of Steel Specifications And Steel Conservation*

By
C. A. DUNLOP
Humble Oil and Refining Company

Introduction

THE standardization committees in the Institute's Division of Production have been actively engaged in cooperative war efforts, as by the simplification in and reduction of material lists to facilitate manufacturing operations, and by assistance given the War Production Board by various members of these committees in establishing a series of National Emergency Steel Specifications to be used for the purpose of increasing the country's output of steel and its products and conserving critical alloys in the interest of National Defense. In addition, a number of these committees have undertaken the preparation of, or have completed codes on the field care and use of oil field equipment, thereby assisting in prolonging the life of equipment and obtaining a consequent reduction in demand for new material.

WPB Steel Specifications

Late in 1941 and before the United States entered the present world conflict, the War Production Board, then the Office of Production Management, being faced with the urgency of increasing the country's production of steel and its products for National Defense, called on the American Society for Testing Materials, Society of Automotive Engineers, and the American Iron and Steel Institute for assistance in establishing a series of National Emergency Steel Specifications to aid the Iron and Steel Branch of WPB in administering steel priorities and allocations. The three organizations named accepted this assignment and agreed to assume full responsibility for developing the desired series of specifications.

The machinery for carrying on this work was set in motion by the appointment of an administrator and administrative committee with the administrator as chairman and representatives of each of the three national technical organizations and of the War and Navy Departments as members. The functions of this committee were: (1) to designate and approve the membership of various technical advisory committees that would perform the actual work of developing the emergency specifications, (2) assign the work to the appropriate committees, (3) review and correlate the reports and recommendations of the technical committees, (4) plan and guide the entire project and assume the responsibility of selecting the minimum number of steel compositions that will satisfy the specifications selected by the various technical committees, and (5) report the recommended list of National Emergency Steel Specifications to the WPB.

Technical advisory committees were designated in accordance with the principal and most urgently needed steel products classified in the NRA steel code, and the NESS organization was established and functioning by April, 1942.

With this beginning each technical advisory committee was directed to proceed as promptly as possible to the selection of a list of steel specifications from specifications then promulgated including those of the War and Navy Departments, with a view to selecting the very minimum number of steel specifications, compositions, and sections necessary to meet the requirements of National Defense, both direct and indirect, with due provision being made for essential civilian needs for steels coming within the scope of each committee. In this work account was to be taken of the status of British and Canadian standardization, and in accordance with the policies established by WPB, the degree of scarcity of critical material and alloying elements, and the need for conserving them for the most effective utilization in the defense program were to be kept constantly in mind. Although the designation of steel specifications and compositions was of primary importance, a reduction of the number of sizes and shapes of steel products was an essential part of the project. It should be understood that the technical advisory committees deal only with the selection of specifications, and the scope of their work does not include priorities nor procurement of either raw or finished materials, nor are they engaged in the formulation of WPB Limitation Orders.

In thus concentrating production upon a reduced number of steels and of sizes and shapes of steel products, the productive capacity of the steel industry and of manufacturing industries using steel for defense requirements could be materially increased within the facilities then available, particularly with respect to alloy steels.

A.P.I. Co-operation

The American Petroleum Institute's Division of Production has actively coöperated with the War Production Board in establishing the desired list of National Emergency Steel Specifications by nominating representatives of the oil industry to various technical advisory committees. To date the representatives have participated, or have proffered their services, in the activities of seven of these committees as follows:

Tubular steel products—TAC No. 11: Selection of the minimum number of specifications to cover fully all classes of tubular steel products was referred to Technical Advisory Committee No. 11 on which the oil industry is represented by H.W. Ladd (Stanolind Oil and Gas Company, Tulsa, Oklahoma, national secretary of the A.P.I. Pipe Committee) and by C. A. Young (secretary, A.P.I. Division of Production, Dallas, Texas) as a consultant member. The work of this committee as affecting oil-country tubular goods is handled by Section 4 of this TAC under the chairmanship of Ladd with committee personnel consisting of representatives of the consuming interests or users, and of pipe manufacturers. The members of Section 4 are also active in the formulation of A.P.I. specifications on tubular goods and, with one exception, are serving on its Engineers Subcommittee on Pipe (H. W. Ladd, chairman), and on its Pipe Manufacturers' Subcommittee (J. Jay Dunn, National Tube Company, Pittsburgh, Pennsylvania, chairman).

Section 4 of TAC-11 considered A.P.I. Std. 5-A, "Casing, Drill Pipe and Tubing" and Std. 5-L, "Line Pipe," as revised at a special joint meeting of the A.P.I. Engineers' and Manufacturers' Subcommittees held in Pittsburgh, Pennsylvania, April 6 and 7, 1942, also all other applicable specifications for the manufacture of oil-country tubular goods that were known to the committee. With the modification that special or non-A.P.I. joints be permitted for casing and provision being made for the manufacture of cement-lined pipe, Stds. 5-A and 5-L were approved and forwarded to the WPB for inclusion in

*Presented before Southwestern District American Petroleum Institute Division of Production, Spring Meeting, Houston, Texas, April 29 and 30, 1943.

the NESS list. In addition, it was recommended by Section 4 that the NESS list include A.S.T.M. specification A-139, "Electric-Fusion-Welded Steel Pipe," and A.S.T.M. specification A-211, "Spiral-Welded Steel or Iron Pipe" to provide for classes of pipe not covered by A.P.I. specifications but which in the larger sizes are extensively used by the oil industry.

Structural steel shapes—TAC No. 4: The Technical Advisory Committee on Structural Steel Shapes tendered its report to the Administrative Committee of NESS, January 3, 1942, in which it was recommended among other specifications that A.S.T.M. specification A-7, "Structural Steel for Bridges and Buildings," and A.S.T.M. specification A-94, "Silicon Structural Steel," be included in the list of National Emergency Steel Specifications. These two specifications are cited in A. P.I. Derrick Standards as controlling the quality of material. In addition, it was recommended and later approved by the WPB that production of structural steel shapes be restricted to those listed in a publication entitled: "National Emergency Steel Specifications—Simplification of Structural Steel Shapes," revised May 11, 1942, and published by the American Iron and Steel Institute.

The producing branch of the oil industry is represented on this Technical Advisory Committee by C. A. Dunlop (Humble Oil and Refining Company, Houston, Texas). Dunlop is national chairman of the A.P.I. Committee on the Standardization of Standard Rigs and Derricks.

Steel bars, forgings, and castings for pressure vessels and pressure piping—TAC No. 17: This technical advisory committee is charged with the designation of specifications on bolting material, forgings and castings, which activity affects the Institute's standards on steel valves and flanges. C. A. Young (secretary, A.P.I. Division of Production) is a consultant member of this group, which consists of a general committee and three sections; namely, Section 1—"Bars and Bolting Materials," Section 2 — "Forgings," and Section 3 —"Castings."

The industry's producing division is also represented on Sections 1 and 3 by W. S. Crake (Shell Oil Company, Inc., Houston, Texas, chairman of the A.P.I. Subcommittee on Valves and Fittings), and the industry's refining division is represented on Section 3 by L. D. Burritt (Standard Oil Development Company, Elizabeth, New Jersey).

Carbon and alloy-steel bars, blooms, billets, and slabs—TAC No. 7: The Technical Advisory Committee on Steel Bars, Blooms, Billets, and Slabs consists of several sections including one on oil tools and drilling equipment of which M. T. Archer (The National Supply Company, Torrance, California) is chairman. This section has been assigned the work of selecting from specifications promulgated, the minimum number of steel compositions that will satisfy the oil industry's need of the raw material that is eventually used in the manufacture of rotary and cable tool drilling equipment, oil well pump parts, sucker rods, etc.

The membership of this TAC section includes representatives of a number of manufacturers of oil field equipment, and the consumer interests of the producing division of the industry are represented by B. B. Wescott (Gulf Research and Development Company, Pittsburgh, Pennsylvania), C. A. Dunlop (Humble Oil and Refining Company, Houston, Texas), and C. A. Young (secretary, A.P.I. Division of Production) as a consultant member.

Carbon and alloy-steel plates—TAC Nos. 1 and 2: Carbon-steel plates and alloy-steel plates are each handled by separate technical advisory committees, and because of the urgency of establishing war emergency specifications for this material, were among the first to be appointed in connection with the NESS project. The reports of these two committees have been submitted to and approved by the WPB, and include A.S.T.M. specifications A-7 and A-10, which are cited in A.P.I. tank standards, No. 12-A, "Riveted Tanks" and No. 12-C "Welded Tanks," as governing the quality of material.

M. B. Higgins (The Texas Company, New York, New York) represents the industry's refining division on the Technical Advisory Committee on Carbon Steel Plates. Nominations for membership on both of these committees of representatives of the industry's producing division were received subsequent to the TAC reports being filed; therefore the appointments were held in abeyance pending additional work or assignment.

Steel wire and wire products: Although it was indicated by the NESS Administrative Committee as a possibility, to date no technical advisory committee has been appointed for the purpose of selecting a list of minimum specifications on steel wire and wire products. The A.P.I. Production Division's nomination of F. H. Schnoor (Standard Oil Company of California, Taft, California, national secretary, A.P.I. Committee on Wire Rope) for membership on this TAC, when appointed, was accepted. It is possible that the non-appointment of this committee is because such activity is now considered unnecessary in view of the recent issuance of a simplified practice on wire rope by the National Bureau of Standards and which is discussed hereinafter in connection with the work of the Institute's Committee on Wire Rope.

Standardization Committee

The standardization work of the A.P.I. Division of Production began in 1919, and is handled by ten national committees, divided into both 100 regional and functional subcommittees, with a total listed membership of over 750.

Today practically all of the principal items of equipment and material used in drilling, production, and oil storage and transportation are covered by 29 specifications or standards with 13 codes covering "recommended practice" in field care and use of oil-field equipment. These standards provide a common meeting ground for the purchaser and seller; they eliminate misunderstanding, provide for interchangeability of product, reduce stocks, establish minimums of quality and/or performance, and permit utilization of material to advantage.

The war found the producing branch of the oil industry well prepared with adequate specifications covering the manufacture of its equipment which in many cases involved considerable reductions in material lists as compared with conditions prior to A.P.I. standardization. As illustrative of this, innumerable requests for A.P.I. specifications have been received by the Dallas office of the Institute from U.S. Army and Navy officials and from contractors on war work, situated in almost every major city in the United States, and from many of the principal foreign countries where the U. S. Armed Forces are operating.

The activities of A.P.I. standardization committees as related to, or influencing the war effort, may be summarized as follows:

Belting, Committee No. 1 (A. H. Riney, chairman): The Institute's belting standard covers V-belts, also several types of flat belting such as rubber, leather, cotton, etc., therefore, the committee's officers feel that the industry is provided with adequate belting specifications, despite the rubber shortage, and no changes are contemplated at present for this standard.

Boilers, Committee No. 2 (C. E. Sutton, chairman): The A.P.I. standard for boilers provides a limited range of definite boiler sizes, and refers to the A.S.M.E. Boiler Code for all details of construction and quality of material, with the exception of a few items peculiar to oil-field boilers. The size and pressure range of A.P.I. oil-field boilers, as now stipulated, are considered sufficient for existing needs, and further simplification does not appear necessary at this time.

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Independence Day, 1943

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Cable tools, Committee No. 3 (E. H. Williams, chairman): This standard is principally dimensional and lists 14 standard sizes of cable tool joints, as compared with over 300 sizes prior to A.P.I. standardization. No further action by this committee on the simplification of sizes of cable-tool joints seems necessary at present.

Derricks, Committee No. 4 (C. A. Dunlop, chairman): The Institute's derrick standard covers major dimensions, chemical and physical properties of materials, allowable working stresses, and includes approved formulas for determining the rated load capacity of derricks and related parts. This specification provides for nine A.P.I. standard height-and-base sizes of derricks, as compared with over 200 sizes prior to A.P.I. standardization and for two types of steel derrick substructures.

As a coöperative war effort, this committee has inaugurated studies intended to conserve material and simplify stocks and manufacturing operations as follows:

1. The simplification of derrick sizes, by deleting 3 A.P.I. height-and-base sizes, retaining 6 sizes as standard.

2. Simplification of pumper-structure sizes by establishing a series of A.P.I. capacities. This study, in coöperation with the A.P.I. Committee on Pumping Equipment, will also include speed reducers.

3. Establish standard dimensions and minimum load requirement of portable drilling and production masts with the intention of improving design and simplifying the numerous styles and sizes currently produced.

Tubular goods, Committee No. 5 (John R. Suman, chairman): The Institute's standards on casing, drill pipe, and tubing (Std. 5-A), and on line pipe (Std. 5-L), cover dimensions, chemical and physical properties, and gauges and gauging practice. This committee has also formulated standards covering threads in fittings; and the major dimensions, physical and chemical properties and pressure rating of pipe-line valves, production valves, and ring-joint flanges.

Among other changes made recently in A.P.I. pipe standards, contributory to the war effort, are the following:

1. Simplification of casing lists, reducing the number of items from over 250 to 95.

2. Simplification in plain-end line pipe list, reducing the number of sizes from 16 to 14, and the number of weights from 121 to 105.

3. Reduction in elongation of Grade J-55 casing as a war measure to conserve manganese, and the adjustment of elongation stipulations on line pipe to agree with other national standards.

4. Manufacture of seamless and electric-weld casing, tubing, and line pipe permitted from acid-bessemer steel, for the duration.

5. Manufacture of electric-weld casing, tubing, and line pipe from open-hearth iron.

6. Manufacture of electric-weld line pipe from electric-furnace steel.

7. Provision for the use of Grade J-55 couplings on Grade N-80 casing without sacrifice in joint strength, for the duration.

8. Revision of line pipe hydrostatic mill-test pressures to obtain agreement with other national specifications.

9. Establishment of uniform pipe thread symbols and nomenclature on pipe threads by the American Petroleum Institute, the American Standards Association, and various governmental agencies dealing with pipe threads.

Proposals now under consideration by the Pipe Committee as an aid in the war effort include the following:

Increase in pressure-temperature ratings of carbon steel and carbon-molybdenum steel pipe-line valves and ring-joint flanges, in accordance with A.S.A. War Standard B16e5 for the duration, and recognition of A.S.A. War Standard B1.4 on fit of straight screw threads for bolting material of production valves and ring-joint flanges.

Rotary drilling equipment, Committee No. 7 (E. J. Nicklos, chairman): The Institute's standard on rotary drilling equipment (Std. 7-B), among other items, provides dimensional standards, including gauges for seven sizes of rotary drilling tool joints in each of three styles (regular, full-hole and internal-flush), for use on seven sizes of internal and external upset drill pipe. The A.P.I. list of seven standard sizes of tool joints replaces several hundred types and sizes in use prior to A.P.I. standardization.

This specification also includes dimensional standards on such items as grief stems, drill collars, slush pumps, piston rods, slush-pump liners, etc.

Wire rope and manila cordage, Committee No. 9 (J. E. Toussaint, chairman): This committee has published two standards: one on wire rope (Std. 9-A), and one on manila cordage (Std. 9-B), both with appendices covering "recommended practice" in the field care and use of this material; both of which have contributed materially to increased life of rope.

Recently the committee has undertaken a revision of its wire rope specification to include a readjustment of strength values, where necessary, and to simplify sizes in order to obtain agreement with a "Simplified Practice" on wire rope, prepared in 1942 at the request of WPB by the National Bureau

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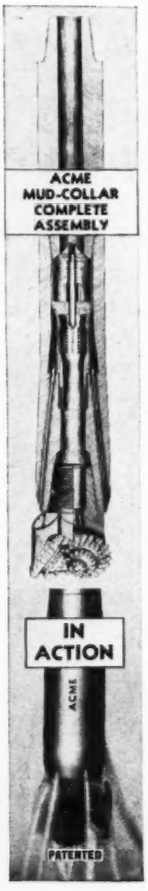

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of Standards in collaboration with the Wire Rope and Strand Manufacturers' Association.

The committee is now conducting an extensive survey of oil-producing interests to determine what action should be taken regarding the specification on manila cordage because of the scarcity of this material as a result of the war, and oil-country drilling requirements having caused cordage manufacturers to deviate from A.P.I. specifications during the last several years.

Pumping equipment, Committee No. 11 (T. E. Swigart, chairman): This committee has adopted eight standards governing manufacture of pumping equipment. Three of these are dimensional only to insure interchangeability; these being oil-well pumps (Std. 11-A), sucker rods (Std. 11-B), and polished rods (Std. 11-D); the others give standard methods for rating internal-combustion engines (Std. 11-C), geared and chain-drive speed reducers (Stds. 11-E and 11-E-1), and hoisting tools for pumping equipment (Std. 11-G).

The standard on oil-well pumps may be cited as typical of results obtainable with dimensional standards. This specification is sufficiently complete to guarantee interchangeability between different manufacturers for the hundreds of items that make up the various types and sizes of oil-well pumps in common use. In the absence of established standardization of this type, users under war conditions would be unable to replace wornout parts unless the manufacturer of the original pump might still have some parts in stock; the A.P.I. standard now makes it possible to utilize practically all of the remaining stocks, either by exchange of finished or semi-finished materials between manufacturers or by the oil producers being able to obtain and use replacements parts from any manufacturer who may have them, regardless of who made the original part. This situation has the important advantage of deferring the time when critical materials must be made available for the manufacture of these items, which are vital to the continued production of oil.

Among other activities of this committee, the following include actions completed or in progress, intended to simplify stocks, and to aid in the war effort:

1. Simplification on sucker rods intended to reduce by about 50 percent the amount of raw stock needed by sucker rod manufacturers.
2. Simplification on polished rods, which is somewhat similar in effect to the action on sucker rods.
3. A simplification study on speed reducers leading to the possible adoption of a limited range of sizes.
4. Preparation of a code of recommended practice in the field care and use of counterbalances.

Tanks, Committee No. 12 (C. C. Ashley, chairman): This committee has adopted four standards on tanks, these being one on riveted tanks (Std. 12-A); one on bolted tanks (Std. 12-B), and two on welded tanks for storage and production service (Stds. 12-C and 12-D). Quality of material is covered by reference to the proper A.S. T. M. specifications.

As a possible aid in the war effort, the committee now has under consideration the formulation of standards on wooden tanks.

After considerable work on the part of this committee on a proposed specification to cover reinforced-concrete oil-storage tanks, the committee dropped the activity by reason of a recent publication by another organization of reasonably adequate data on reinforced concrete tanks; this in order to avoid duplication and to conserve manpower.

Acknowledgment

The author hereby expresses appreciation to the management of Humble Oil and Refining Company for permission to prepare and publish this paper, and to J. E. Stillwell (A.P.I. Division of Production, Dallas, Texas) for his assistance in supplying most of the information.

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These are just a few of the plus values of "Oilwell's" 10-Point Supply Service. You'll discover the others when you visit an "Oilwell" store—where you are a stranger only once.

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To assure prompt deliveries and provide the best possible care and protection for materials in stock, "Oilwell" has a new and efficient warehouse system. Each division has a large central warehouse with reserve stocks of miscellaneous supplies for the branch stores in its territory. Each division also has a number of district warehouses in which machinery and sucker rods are stored under cover. These warehouses are located at points assuring convenient shipping-hauls direct to customers' leases.

4. CONVENIENT STORE LOCATIONS

"Oilwell" field stores are located where they will provide maximum convenience for the greatest possible number of operators. It would not be feasible to maintain a store in every field, but "Oilwell" stores are located where they can serve all oil and gas fields in the United States and Canada.

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"Oilwell's" field engineers are trained and experienced in helping customers in the proper selection, installation, operation and maintenance of equipment. Many times their recommendations result in the elimination of equipment failures and the lowering of operating costs. They are always available to plan and supervise turnkey installations.

6. PRODUCT DESIGN AND METALLURGY KEYED TO YOUR NEEDS

"Oilwell's" supply service includes the designing and development of new equipment and improved materials that will best suit specific oil and gas field needs. Many outstanding advancements have been pioneered by "Oilwell".

7. EXTENSIVE MANUFACTURING AND TESTING FACILITIES

Much of the equipment distributed by "Oilwell" is made right in "Oilwell's" own plants, where experienced craftsmen with modern machine tools build products--from the design up--for oil field service. Careful inspecting and extensive testing assure high standards of quality and performance. Contributing much to "Oilwell's" own facilities are the raw material resources, the manufacturing capacity and the research and testing laboratories of United States Steel Corporation.

8. HIGHEST GRADE SUPPLIES FOR OIL AND GAS FIELD NEEDS

In purchasing many thousands of items for resale, "Oilwell" feels a genuine responsibility to its customers and buys only from sources of proved reliability. Just as materials purchased for fabrication in "Oilwell" plants are carefully inspected for uniformity of quality, so are those items which are stocked for sale to "Oilwell" customers.

9. PROMPT AND UNDERSTANDING CREDIT SERVICE

"Oilwell," through years of experience, has gained a thorough understanding of the oil man's financial problems, and has the resources and facilities for rendering efficient credit service.

10. 81 YEARS OF PRACTICAL EXPERIENCE

The experience gained in serving the oil industry continuously throughout all stages of field developments, wars and other emergencies of the past 81 years, makes "Oilwell" better able to serve its customers under today's unusual conditions. Carrying on under emergency restrictions is no new experience for "Oilwell".

OIL WELL SUPPLY COMPANY

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Mud Acid—Its Theory and Application to Oil and Gas Wells*

By
PHIL J. LEHNHARD
Dowell Incorporated

Abstract

IT IS the purpose of this paper to show that large increases in the productivity of sand wells treated with mud acid are due to the reduction or elimination of abnormally high pressure drops near the bore hole of the well; and that only small increases in productivity may be obtained in most instances unless such abnormal pressure drops occur. It is shown that some oil sands contain clay or bentonitic material that has the ability to hydrate or swell when in contact with water, and that hydration of such materials in the sand will cause a reduction in its permeability. The paper points out that screens or perforated liners, gun perforations, and hydration of clay materials in the sand near the bore hole may all cause abnormally high pressure drops near the well.

It is also intended that the paper should be a resumé of field experience with mud acid to date, together with conclusions reached as a result of more than two years of the commercial application of mud acid to oil and gas wells.

Introduction

Several years ago, mud acid was first introduced in the Texas and Louisiana Gulf Coast oil fields,[1] and since that time has been used in increasing quantities. The actual mechanics of increasing the production of wells producing from a sand formation is very different from that involved in wells producing from limestone formations, even though both require the solution of certain parts of the formation by chemical means. In limestone formations, the material that is dissolved by acid treating is principally calcium carbonate; whereas in sand formations the material that is dissolved by treatment with mud acid is principally clay and bentonitic materials.

Clays and Bentonitic Materials

It is well known, of course, that rotary drilling muds contain large percentages of clays, some of which have high colloidal properties, such as the pure bentonites, and others that possess these colloidal properties to a lesser degree. X-ray analysis shows that the clay compounds that are principally found in rotary drilling muds are montmorillonite, beidellite, illite, and kaolin.

It has been found by X-ray analysis that many sand formations, particularly those in the Texas and Louisiana Gulf Coast, contain very appreciable quantities of these clay materials, with the percentage of this material present in oil sands varying from zero to as much as 50 percent of the formation by weight.

Table 1 shows the X-ray analyses of a number of typical Texas and Louisiana Gulf Coast oil-producing sands; also the analyses of several typical drilling muds and commercial clays used for drilling muds.

Properties of Mud Acid

Mud acid is a mixture of hydrochloric acid and certain other chemicals, together with chemical agents added to give it the proper demulsifying and surface tension characteristics. Mud acid will dissolve any of the materials that are soluble in hydrochloric acid, such as limestone, calcium carbonate scale, and cement. In addition, it has the property of dissolving clay materials such as those found in sand formations and drilling muds: montmorillonite, beidellite, illite, metahalloysite, muscovite, kaolin, and others. Mud acid will also dissolve quartz sand, although to a limited extent. Tables 2 and 3 show the solubility of typical Gulf Coast drilling muds, and oil-producing formations in mud acid.

Another property of mud acid is that in cases where an excess of bentonite is encountered, and the available acid will dissolve only a part of it, the mud acid will destroy the colloidal or swelling properties of the entire mass. For example, aquagel bentonite that has been treated with mud acid will filter water rather easily, even though only a small part of the entire mass has been dissolved. On the other hand, bentonite that has not been treated will hardly filter water at all. This same effect can be observed in the action of mud acid upon mud cakes made by squeezing the water out of the mud. Mud acid will increase the permeability of the mud cake from practically zero to a very high value, even though a very small percentage of the mud is dissolved. Table 4 shows the effect of mud acid upon the permeability of the mud cake formed by a number of Gulf Coast drilling muds.

Present laboratory data indicate that 1 gal. of mud acid will dissolve approximately 0.3 lb. of these clay materials. The rate of the reaction of mud acid upon clay is not affected by pressure. Temperature, however, does have a very considerable effect upon the rate of reaction. Laboratory tests show that, by increasing the temperature of the acid from 70°F. to 200°F., the rate of reaction of mud acid upon clay will be increased by 48 percent. The rate of reaction is also dependent upon the amount of clay that is in contact with a given volume of mud acid; the higher the ratio of clay to acid, the faster the acid spends itself. Theoretically, mud acid that is in contact with a normal amount of clay in the formation at 150°F. should spend itself in about one minute; that is, the clay solvent should be spent in about that time. This has been substantiated by laboratory tests under conditions comparable to those in the formation.

The effect of mud acid upon the permeability of sandstone cores can be easily demonstrated in the laboratory. A large number of sandstone cores, containing varying percentages of clay material, have been treated with mud acid with permeability increases ranging from zero to well over 1000 percent. The average increase in permeability obtained on this type of core is probably about 400 to 500 percent. One interesting result observed in the treatment of cores with mud acid is the effect of a combination of mud acid and a wash solution of HCl upon the increase in permeability of cores that contain varying percentages of carbonate material.

Tests were run on 11 cores having an average solubility of 2.6 percent in hydrochloric acid and 12.4 percent in mud acid. (The hydrochloric acid soluble material is principally calcium carbonate, whereas the mud acid soluble material is clay plus the calcium carbonate,) with the following results:

Acid used in treating	*Increase in permeability, percent*
Hydrochloric acid	3.8
Mud acid	110
Hydrochloric acid followed by mud acid	101
Mud acid followed by hydrochloric acid	280

Tests also were run on 23 cores having an average solubility of 12.4 percent in hydrochloric acid and 22.2 percent in mud acid, with the following results:

Acid used in treating	*Increase in permeability, percent*
Hydrochloric acid	145
Mud acid	15 decrease
Hydrochloric acid followed by mud acid	195
Mud acid followed by hydrochloric acid	346

*Presented before American Institute of Mining and Metallurgical Engineers, Austin, Texas, October 29-31, 1942.

These results indicate that, both in formations containing high and low percentages of calcium carbonate, best results can be expected from treatments with mud acid followed by a wash solution of 15 percent HCl. They also indicate that, in the treatment of cores with a high lime content, fair results can be obtained by the use of 15 percent HCl alone. Further, they indicate that, in formations containing a high percentage of calcium carbonate, a temporary decrease in permeability may be obtained by treating with mud acid unless the formation is first treated with a wash solution of hydrochloric acid.

TABLE 2

Solubility of rotary drilling muds and commercial clays in 15 percent HCl and mud acid

Mud No.	Pool	County and State	Composition		Percent solubility of dry solids in	
			Percent water	Percent solids	Mud acid	15 percent HCl
1	English Bayou	Calcasieu, La.	65.5	34.5	67.72	15.15
2	University	Baton Rouge, La.	70.5	29.5	51.20	10.80
3	Port Barre	St. Landry, La.	63.9	36.1	50.44	10.85
4	Port Barre	St. Landry, La.	63.8	36.2	43.49	9.40
5	Jennings	Acadia, La.	93.1	6.9	52.82	11.49
6	Eola	Avoyelles, La.	74.5	25.5	46.17	7.65
7	Tepatate	Acadia, La.	76.0	24.0	47.07	10.39
8	Ainse La Butte	Lafayette, La.	47.2	52.8	30.40	7.63
9	Paradise	St. Charles, La.	64.5	35.5	61.93	10.00
10	Wildcat	St. Marys, La.	50.5	49.5	48.28	8.87
11	Wildcat	La Fourche, La.	61.3	38.7	55.32	11.19
12	Stark	Calcasieu, La.	61.3	38.7	54.12	8.79

Increasing Well Productivity

"Critical Zone" is a rather indefinite term that refers to the zone in the immediate vicinity of the bore hole of a well where fluid velocities and pressure drops are extremely high. For the purposes of this paper the "Critical Zone" is assumed to be that zone within a 1-ft. radial distance of the bore hole of the well.

The mechanics of increasing well productivity in limestone and sand formations is very different. Oil and gas reservoirs composed of limestone generally have a very irregular permeability pattern, great variations in permeability varying from zero in dense parts of the lime to many thousands of Darcys in cracks or crevices; and, in most cases, porous zones filled with oil or gas that are not interconnected, or are blocked off from the main flow channels into the well by very small restrictions. This results in a condition of almost linear flow into the well,[2] and the removal of a part of the flow restrictions and the enlargement of the main flow channels into the well by acidizing results in large increases in production.

Oil and gas reservoirs composed of sandstone generally have a very uniform permeability pattern, fairly uniform permeabilities and continuous porosity that result in a condition of radial flow into the well,[2,13] in much the same manner as the spokes of a wheel converge toward the hub from the rim. Conditions are sometimes encountered in the hard, dense sandstones of Wyoming and Montana, where, even though the sand has a uniform permeability pattern and fairly uniform permeabilities, the flow into the well is more like that from a limestone reservoir due to the presence of cracks or fractures in the body of the sand.[3] Except in cases where fractures occur, increased well productivity by acid treatment of sand formations is due to changes in permeability that only affect the critical zone in a radial flow system.

TABLE 1

X-Ray analyses of typical Gulf Coast formations, drilling muds, and commercial clays

Field	Formation	Depth, ft.	Quartz	Composition, percent by weight			
				Clay	Albite	Pyrite	Misc.
Sand formations							
Barbers Hill	Oligocene	....	70	1a I	15		
Ganado	Oligocene	5100	60–70	20–40 K			
Golden Meadows	Miocene	5300	60–70	20–30 B	10		
Lake St. John	Wilcox	3398	90	10 M			
		3438	80	15 M	5		
Loma Novia	Gov't wells	2732	45	45 MM	10		
		2750	50	15 MM	30		5 C
Manvel	Marginulina	5355	60–70	20–30 B	5–10	1	
		5375	50–60	30–40 B	5–10		
Segno	Wilcox	8040	60–80	10–20 MM		5–10	5–10 X
		8030	70–80	10–20 MM			5–10 X
Sheridan	Wilcox	9384	50–65	15–25 X	20–30		
		9405	65–80	10–15 K	10–20		
Villa Platte	Wilcox	9844	70–90	10–20 H	5–10		
		10182	65–85	10–20 H	5–10	3–5	
		10207	60–80	20–30 H	5–10	1–3	
	Haas	9014	70–90	10–20 M	5–10		
Wharton	Kountz	5158	90	10 K			
	Lancaster	5140	50	50 K			
Wildcat	Eocene	....	50–70	20–30 MM	10–20		
Drilling muds							
Hastings field			55	25 I	5		15 C
Golden Meadows field			50–60	30–40 B	5–10		
East Placedo			20	60 B			20 C
Hackberry			35	60 B			5 C
Commercial Clays							
Dakota Bentonite				100 MM			
Grundite from Illinois			60	40 I			
Kentucky Ivory Ball Clay			50	50 K			
Monroe Wad Clay			50	50 K			
Muroc Green				100 MM			
Tennessee No. 1 S.G.P.				100 K			
Tennessee No. 7 Ball Clay			20	85 K			
Volcanic Ash from Gulf Coast				100 MM			

B—Beidellite H—Metahalloysite K—Kaolin MM—Montmorillonite
C—Calcite I—Illite M—Muscovite X—Unidentified

Critical Zone Permeability

In the following section of the report the results of calculations of theoretical well productivities under varying conditions in the critical zone are given, and also pressure gradient curves based on these calculations. In order to make these calculations, it was necessary to make certain assumptions as to well conditions, which were:

1. An arbitrary drainage radius, of 250 ft.
2. Well bore diameter of 0.25 ft.
3. Uniform permeability in the sand outside of the critical zone boundary.
4. Flow rates in the sand are of such an order as to be within the limits of the validity of Darcy's law.
5. The well produces gas-free oil.
6. The well completely penetrates the producing sand.

In making comparisons of well productivities caused by variations in the permeability of the critical zone, the assumption of an arbitrary well drainage radius should not introduce too great an error, provided the radius is large, as the results are not in themselves quantitative but are only comparative. The assumption of uniform permeability is reasonable for the same reason. The assumption that Darcy's law is valid seems justified. Most wells do not produce gas-free oil; however, this assumption is made in order to simplify the calculations, and it is believed that for comparative purposes such an assumption is in order. Many wells completely penetrate the sand, but in cases where they only partially penetrate it or only produce from a portion of it, a greater percentage of the total pressure drop through the sand will be concentrated in the critical zone so that variations in the permeability of the critical zone will have a more

TABLE 3

Solubility of producing formations in 15 percent HCl and mud acid

Pool	Area	Formation	Depth, ft.	Average solubility in percent	
				Mud acid	15 percent HCl
Alice	Texas Gulf Coast		5150	51	17
Bexar County	Southwest Texas		963	66	17
Carrizo	Texas Gulf Coast			17	2
High Island	Texas Gulf Coast	Miocene	4680-5440	32-60	2-10
Luby	Texas Gulf Coast	Oakville	5612-5632	30-60	0-9
Agua Dulce	Texas Gulf Coast	Catahoula	4735-4765	43	30
			6360-6390	41-60	14-46
			5485-5500	53-61	8-12
Angleton	Texas Gulf Coast	Frio	9900-10490		Less than 2
Ganado	Texas Gulf Coast	Frio	5069-5108	23-33	2-3
Esperson Dome	Texas Gulf Coast	Cockfield	7025	20	2
			8500	22-42	3-5
Joes Lake	Texas Gulf Coast	Wilcox	7686	15	1
Loma Novia	Texas Gulf Coast	Gov't Wells	2720-2850	20-60	2-7
Manvel	Texas Gulf Coast	Marginulina	5355-5389	23-42	2-4
Louise	Texas Gulf Coast	Frio	5150	22	4
Nueces County	Texas Gulf Coast	Frio	5300-5323	45-50	9-24
N. Sweden	Texas Gulf Coast	Jackson	4750-4790	50	16-30
Old Ocean	Texas Gulf Coast	Frio	10065-10092	45	34
				25	1
Placedo	Texas Gulf Coast	Frio	4747-4765	24	4
Rowan	Texas Gulf Coast	Frio	8600-9220		2-7
Rincon	Texas Gulf Coast		3809-3927	60	24
Segno	Texas Gulf Coast	Wilcox	8030-8090	35-40	4-13
Starr County	Texas Gulf Coast		1930	63	24
Turkey Creek	Texas Gulf Coast	Frio	5860	50	
White Creek	Texas Gulf Coast	Gov't Wells	1500	45	1
Black Bayou	La. Gulf Coast	Miocene	4326-4402	24-55	3-17
Charenton	La. Gulf Coast	Miocene	950	44	4
Eola	La. Gulf Coast	Sparta	5887-6010	20-65	5
		Wilcox	8500-8600	16-25	2-8
Golden Meadow	La. Gulf Coast	Miocene	5300	24	1
Ville Platte	La. Gulf Coast	Haas	8832-8837	21	2
		Taite	9088-9097	23	1
		Wilcox	9900-10300	22-35	3-5
Long Lake	North Texas	Woodbine	5294-5304	30	3
East Texas	East Texas	Woodbine	3600	8-45	1-28
Hawkins	East Texas	Woodbine	4419-4425	15-25	5
Tinsley	Mississippi	Eutaw	4931-4967	20-27	12-27

pronounced effect upon well productivity.

Theoretical calculations show that in wells having a uniform permeability throughout the sand, half of the pressure drop through the sand occurs within an 8-ft. radius of the bore hole, and large scale experiments by Uren verify the high concentration of pressure drop near the bore hole.[2,13] Thus, if the permeability of the zone within an 8-ft. radius of the bore hole were increased to infinity, half of the pressure drop would be removed, and the productivity of the well would be doubled. In the acid treatment of wells, sufficient amounts of acid to penetrate 8 ft. from the bore hole are not used and the permeability of that zone which the acid penetrates is not increased to infinity. As a result, it can be easily seen that the increase in productivity that might be obtained in a well that had a uniform permeability throughout the sand would be much less than double.

If for any reason the permeability of the sand in the critical zone should be less than that in the rest of the sand, or bottom-hole equipment in the well should cause excessively high pressure drops in the sand near the bore hole, the possible increase in well productivity that might result from changes in the permeability of the sand in the zone near the bore hole is much greater.

The theoretical production increase that can be obtained by opening up or increasing the permeability of a small zone close to the bore hole *that has been plugged by drilling or production methods*, or *restricted by certain mechanical completion methods and equipment*, can be calculated mathematically. It also can be demonstrated in the laboratory by large scale laboratory experiments, although very little work of this type has been carried on in the laboratories. As an illustration, the following are a few examples of the calculated production increase that might be obtained under various well conditions:

Case No. 1—A well completed with open hole, no screen or perforated pipe and completed in such a manner that no plugging of the sand near the bore hole occurs:

Permeability increase in critical zone (1 ft. radius from bore hole), percent	*Calculated increase in productivity of well, percent*
100	13
300	21
900	27
Infinite	31

Case No. 2—A well completed with open hole, no screen or perforated pipe. Due to certain drilling or production methods, the permeability of the sand within a 1-ft. radius of the bore hole has been reduced 96 percent.

Permeability increase in critical zone (1 ft. radius from bore hole), percent	*Calculated increase in productivity of well, percent*
100	82
300	208
900	425
Increased to original value	900

Case No. 3—A well completed in such a manner, and with such mechanical completion equipment, that 75 percent of the pressure drop occurs in the sand within 1 ft. of the bore hole. Permeability of the sand in the 1-ft. zone is the same as that of the sand in other parts of the drainage area:

Permeability increase in critical zone (1 ft. radius from bore hole), percent	*Calculated increase in productivity of well, percent*
100	61
300	132
900	212
1900	256

The curves in Fig. 1 and Fig. 2 show this graphically. Curve "A" in Fig. 1 shows the normal pressure gradient around a well that has been completed with open hole, and in which there is no plugging of the sand near the bore hole. Curves "B," "C," and "D" show the effect of increasing the permeability of the critical zone upon the pressure gradient and the specific productivity index of the well. Curve "A" in Fig. 2 shows the pressure gradient around a similar well in which the critical zone has been 96 percent plugged by drilling or production methods. Curves "B," "C," and "D" of Fig. 2 show the effect of increasing the permeability of the critical zone that has been plugged, on the pressure gradient and the specific productivity index of the well.

Abnormal Pressure Drops

Investigations of the last few years by the leading oil companies and service companies, particularly in connection

TABLE 4

Effect of mud acid on the permeability of mud cakes

Mud No.	Pool	County and State	Water flow through mud cake in cc. per min.		Percent increase in flow rate or permeability by mud acid treatment
			Before mud acid	After mud acid	
1	English Bayou	Calcasieu, La.	0.466	3.67	690
2	University	Baton Rouge, La.	1.460	46.0	3100
3	Port Barre	St. Landry, La.	1.130	44.0	3800
4	Port Barre	St. Landry, La.	1.55	80.0	5000
5	Jennings	Arcadia, La.	1.00	8.7	770
6	Eola	Avoyelles, La.	0.40	13.35	3250
7	Tepetate	Acadia, La.	1.00	166.6	16500
8	Ainse La Butte	Lafayette, La.	1.07	125.0	12400
9	Paradise	St. Charles, La.	0.333	85.0	2450
10	Wildcat	St. Marys, La.	0.67	150.0	22500
11	Wildcat	La Fourche, La.	0.50	Infinity	Infinity
			Mud cake disintegrated after treatment		
12	Stark	Calcasieu, La.	1.67	250.0	15000

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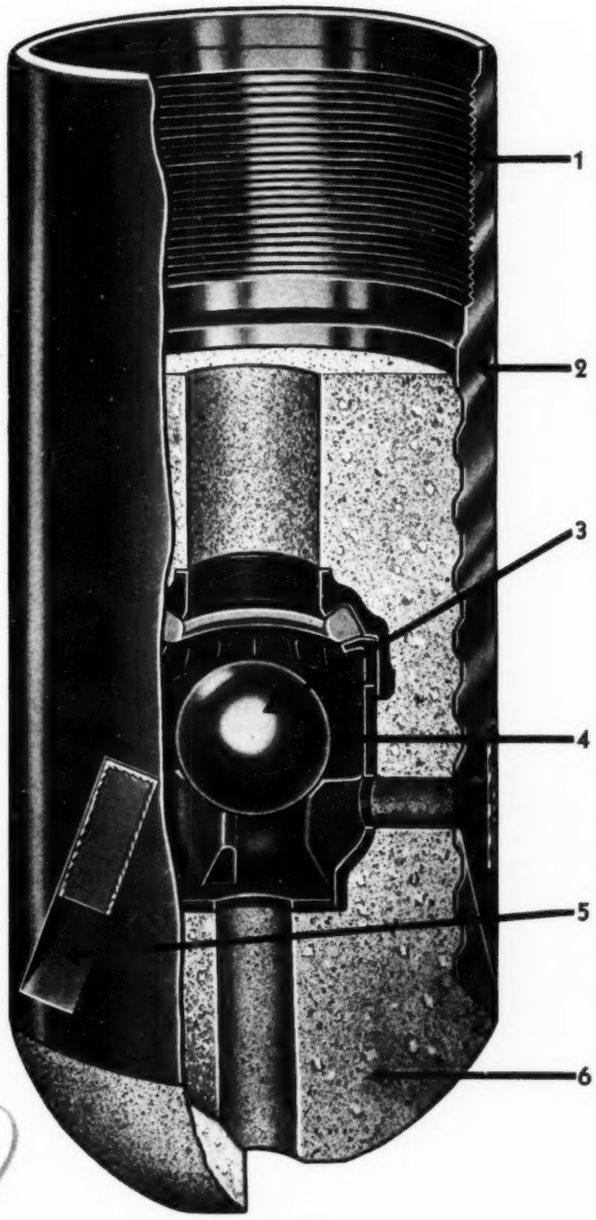

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Baker Cement Wash-Down Whirler *Float Shoe

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1. THREADED CONNECTION FURNISHED TO FIT ANY TYPE CASING. Baker Floating Units can be furnished with threaded connection to fit the specifications of your casing. (Float collars can be furnished with both "female" and "male and female" threaded connections. Manufacturing precision assures thread uniformity and accuracy.

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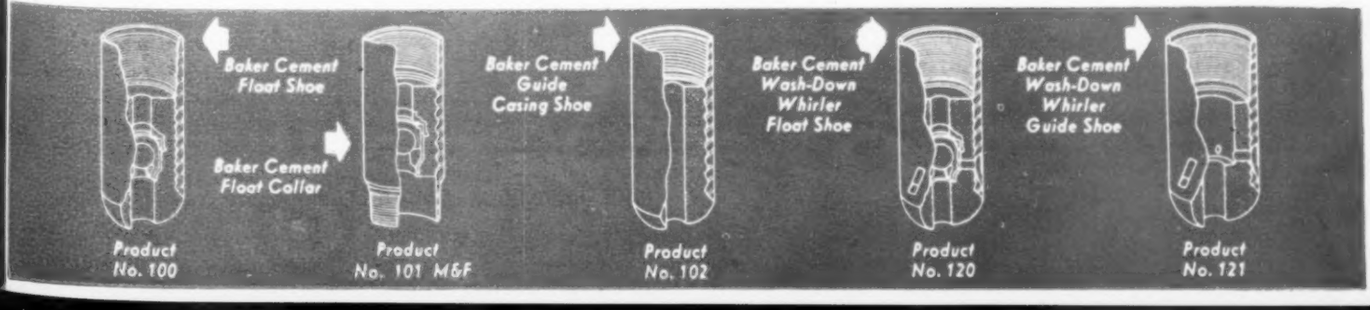
4. AMPLE CIRCULATION AREAS. The correctly designed, streamlined Valve Assembly provides passageways ample for any circulating or cementing operation . . . a fact attested to by actual field performance under the most severe operating conditions.

5. BAFFLED WHIRLER PORTS. These whirler ports provide the important wash-down whirler action so advantageous in circulating and cementing operations. When the fluid strikes these baffled ports, a downward and then an upward whirling motion results. In running in, this whirling action provides a means of effectively washing away bridges. During cementing, the whirling action, imparted first to the fluid preceding the cement slurry and then to the slurry itself, properly prepares the hole to receive the cement. It then assures best possible distribution of a uniform body of cement around the shoe and the shoe joint, reducing the hazard of channeling to a minimum. Here is the ultimate in cementing efficiency.

6. EASY DRILLABILITY. Complete and easy drillability results from the internal construction of Baker-Formula Concrete and Plastic . . . the Plastic BALL-TYPE Valve Assembly being set on end in the concrete plug to present a minimum cross-sectional area to the drilling bit. The concrete and the Plastic are quickly and easily drilled up and circulated out of the hole.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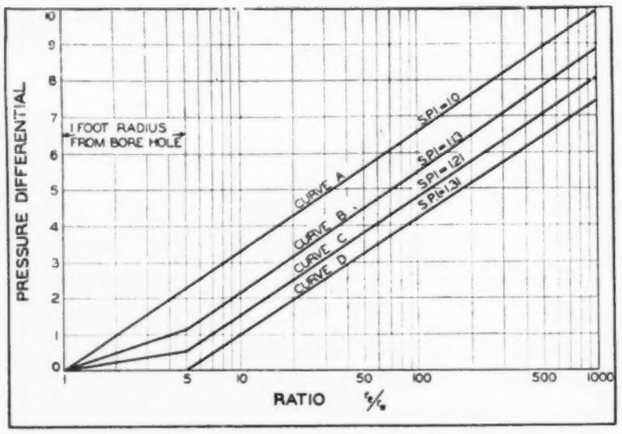


Fig. 1. Effect of mud acid on productivity

Theoretical pressure gradient around a well for varying permeability conditions in a 1-ft. radial zone from the well, at constant flow rate.

Curve A = Normal pressure gradient around well having open hole and clean sand. Specific productivity index = 1.0.

Curve B = Pressure gradient if permeability in 1-ft. radial zone is increased by 100 percent. Specific productivity index = 1.13.

Curve C = Pressure gradient if permeability in 1-ft. radial zone is increased by 300 percent. Specific productivity index = 1.21.

Curve D = Pressure gradient if permeability in 1-ft. radial zone is increased to infinity. Specific productivity index = 1.31.

r_e = Radial distance from well.

r_w = Well radius

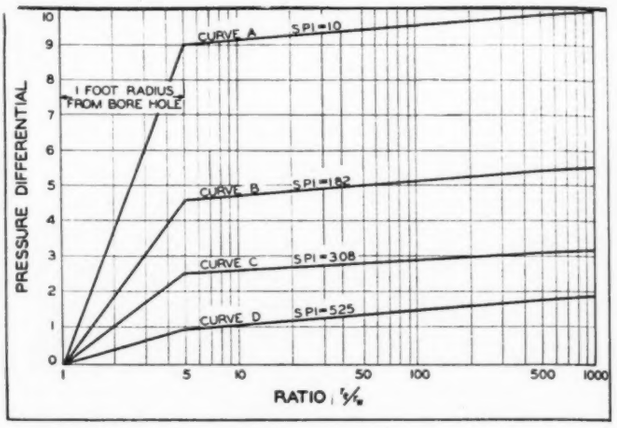


Fig. 2. Effect of mud acid on productivity

Theoretical pressure gradient around a well in which the permeability of a 1-ft. radial zone around the bore hole has been 96 percent reduced by drilling or production methods, and the effect of increasing the permeability upon the pressure gradient, at a constant rate of flow.

Curve A = Permeability of 1-ft. radial zone 96 percent reduced by drilling or production methods. Specific productivity index = 1.0.

Curve B = Permeability of 1-ft. radial zone increased 100 percent by acidizing. Specific productivity index = 1.82.

Curve C = Permeability of a 1-ft. radial zone increased 300 percent by acidizing. Specific productivity index = 3.08.

Curve D = Permeability of a 1-ft. radial zone increased 900 percent by acidizing. Specific productivity index = 5.25.

r_e = Radial distance from well.

r_w = Well radius

with the acidizing of wells producing from sands, have indicated that abnormally high pressure drops do occur in the critical zone of some wells.

There are several ways in which abnormally high pressure drops may be created near the bore hole of a well, which are:

1. Swelling of bentonitic material in sands through contact with water,[4] and possibly the infiltration into the sand of very small mud particles from the drilling mud.[6,7,8,9,12]

Salt water, as well as fresh water, will cause bentonite to swell, although not nearly as much, and the degree of swelling is dependent upon the concentration of the salts in the water.[4] Salt water will cause a reduction of permeability in some sands. However, no tests made to date indicate that salt water will stop entirely the flow through a sand. There are several ways in which either fresh water or salt water may be preferentially introduced into the critical zone of a well. Those recognized at present are:

A. Loss of water into the formation when working over a well using water as a drilling fluid.

B. Circulation of water from a high-pressure water sand into a low-pressure oil producing sand, due to casing leaks, etc.

C. Infiltration of water from drilling muds during drilling operations.[6,7,8,9,12] The amount of water entering the formation from a drilling mud depends upon the mud characteristics and the length of time that the mud is in contact with the sand; also the differential pressure exerted against the sand. Sands that have been drilled through, with drilling proceeding on to a lower depth without setting pipe, will contain much more infiltrated water from the mud than those sands that are only partially penetrated or in which the drilling is stopped as soon as the sand has been drilled through.

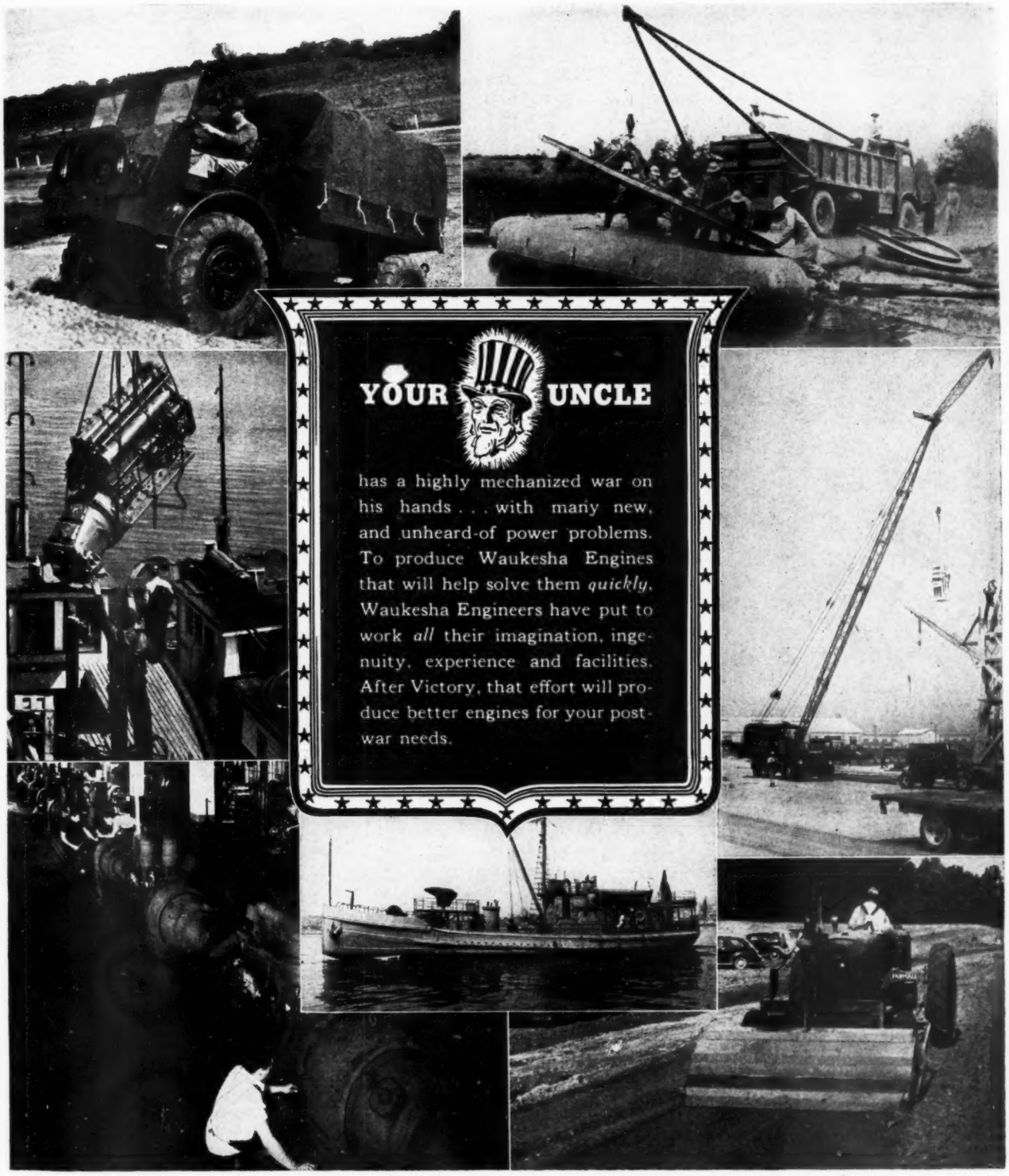
D. The release of entrapped interstitial water near the bore of the well, due to the low pressures in this zone during flow into the well. Also, the flushing of entrapped interstitial water from tight sections, due to the high-pressure differentials near the bore hole during flow into the well.[15]

E. The encroachment of bottom water into the oil sand near the bore hole by "water coning," due to the lowered pressure in this zone during flow into the well.[2]

2. Preferential deposition of some of the heavier hydrocarbon constituents of crude oil near the bore hole due to reduction of the pressure in this area during flow into the well. Very little is known at the present time about the actual mechanism of the plugging of sand by the preferential deposition of some of the heavier hydrocarbons of crude oil. However, investigations along this line are now being carried on by several laboratories. The best indication of this deposition is the fact that treatments using a combination of kerosine and paraffin solvent produce good increases in the production of many wells.

3. Mechanical completion methods involving the use of perforated liners or pipe, or wire wrapped screen.[5,8] It is a rather obvious fact that the presence of perforated liners or screens and also the practice of gun perforating through the casing in a well would cause increased pressure drops in the sand near the bore hole. However, there is some evidence to indicate that the explosive effect of a bullet penetrating into the sand may affect the sand in such a way as to partially offset the effects that would be obtained by perforated pipe alone.

4. Small penetrations into thick bodies of sand.[2] In wells that do not completely penetrate a sand having vertical as well as horizontal permeability, a condition of spherical flow exists.[2] In other words, the oil flowing in the formation approaches the well from three directions, rather than two. In cases of small penetrations into such a sand there would be a much higher pressure drop in the vicinity of the well than in the case of a well that was drilled through the sand, so large increases in the permeability of the sand close to the well should result in good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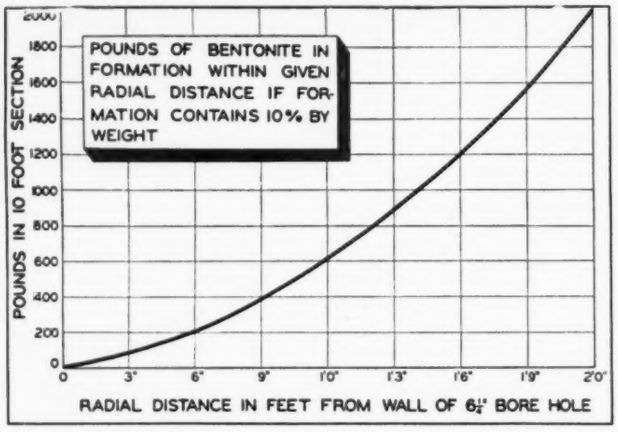
POUNDS OF BENTONITE IN FORMATION WITHIN GIVEN RADIAL DISTANCE IF FORMATION CONTAINS 10% BY WEIGHT
POUNDS IN 10 FOOT SECTION
RADIAL DISTANCE IN FEET FROM WALL OF 6½" BORE HOLE

Fig. 3. In a sandstone 10 ft. thick containing 10 percent bentonite by weight there are 610 lb. of bentonite within a 1-ft. radius of the bore hole

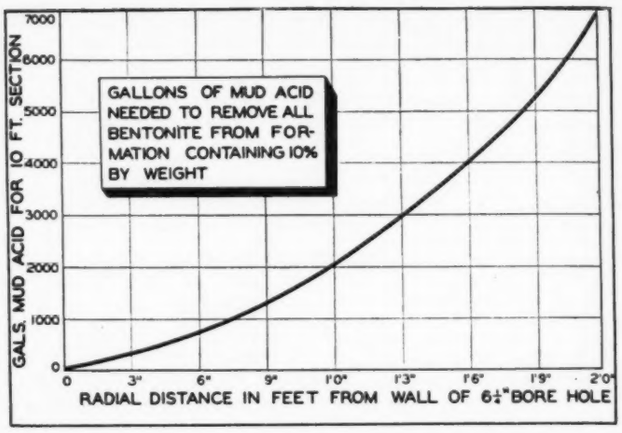
GALLONS OF MUD ACID NEEDED TO REMOVE ALL BENTONITE FROM FORMATION CONTAINING 10% BY WEIGHT
GALS. MUD ACID FOR 10 FT. SECTION
RADIAL DISTANCE IN FEET FROM WALL OF 6½" BORE HOLE

Fig. 4. One gallon of mud acid will dissolve 0.33 lb. of bentonite. For the sand conditions above 2000 gal. will dissolve all the bentonite within a 1-ft. radius of the bore hole

increases in the productive capacity of the well.

Effect of Mud Acid

Mud acid acts in two ways to increase the productivity of wells, both of which involve the solution of silt and clay, or bentonitic material in the sand:

1. The productivity of the well may be *reduced* by the swelling of the bentonitic-like material in the critical zone. The solution of this material by mud acid removes the *cause* of the low productivity of the well.

2. Where a high pressure drop in the sand near the bore hole is caused by *mechanical methods or equipment*, the solution of the bentonite-like materials from the sand in the critical zone causes an increase in the permeability of the sand in this zone of sufficient magnitude as to *compensate* for the low productivity due to the completion method.

Field and Laboratory Evidence

The theory that certain sand conditions and well completion methods cause abnormally high pressure drops near the bore hole, and that mud acid increases well productivity by eliminating or compensating for the abnormal pressure drop near the hole, is substantiated both by laboratory and field evidence.

In the laboratory the clay material that is found in oil sands has been segregated from the sand by differential settling and centrifuging, and tests show that some of this material will swell as much as 8 to 10 times its dry volume when in contact with water; also that this material that exhibits the swelling properties of bentonite is almost completely soluble in mud acid. The effect that this swelling could have on the permeability of oil sands can be easily imagined.

Tests conducted in the Dowell laboratories have shown that this reduction in permeability is actually obtained: and, further, that in some cases fresh water will stop the flow through sand or cores completely. Leverett,[11] has also observed this reduction in permeability, due to fresh water, in some of the laboratory work that he has done, both in actual producing sand and in a clean silica sand to which has been added 5 percent bentonite.

It is common knowledge throughout the oil fields that the flooding of oil sands with water often results in large decreases in production. Electric logs indicate that considerable quantities of water from drilling muds enter most sand formations during the drilling.[14, 23]

Some large scale experimental work has been done on the effect of perforated liners on pressure gradients into the well. Frank G. Miller of the U. S. Bureau of Mines has shown in some of his work,[5] that in some cases comparable to those actually encountered in the field, slotted liners may cause as much as 80 percent of the pressure drop or energy loss to be concentrated in the sand within a 1-ft. radius of the bore hole of the well.

The fact that good production increases can be obtained upon some sand wells by opening up or increasing the permeability of the zone close to the bore hole is substantiated by the results obtained in some fields by enlarging the bore hole, or making artificial cavities in the sand.[15, 16, 17] In the Loma Novia field of Southwest Texas, The Texas Company, and several other operators, have obtained very good increases in production from their wells by the method of enlarging the bore hole with a special type cable-tool bit and gravel-packing their wells.[15] The average increase in the diameter of the holes in this work is about 1 ft., and in some cases production increases of as much as 800 percent have been obtained. Kenneth E. Hill, of the College of Mining, University of California, in a recent paper on the subject of "Gravel-Packing,"[17] reports a number of wells in which production was very appreciably increased by under-reaming and gravel-packing.

Further evidence seems to be the fact that calculated productivities of wells, based on core analysis, are generally much higher than those actually obtained, as in making calculations of productivities it is assumed that the sand has a uniform permeability throughout and that abnormally high pressure drops due to completion methods or equipment do not occur. Sherborne shows in a recent report[12] a comparison of the calculated theoretical productivity and the actual productivity of 52 wells. The best known methods of coring and sampling were used when these wells were drilled-in, and the theoretical productivity of these wells was calculated using the most accurate methods and formulas known at that time. The wells were then tested carefully and their actual productivity measured. In all cases the actual productivity of the wells was lower than that calculated theoretically. The maximum difference was in a case where the calculated productivity was 264 times the actual, and the minimum difference was in a case where the calculated productivity was 3.16 times the actual productivity. The average well had a calculated productivity 45 times as large as the actual value. This same

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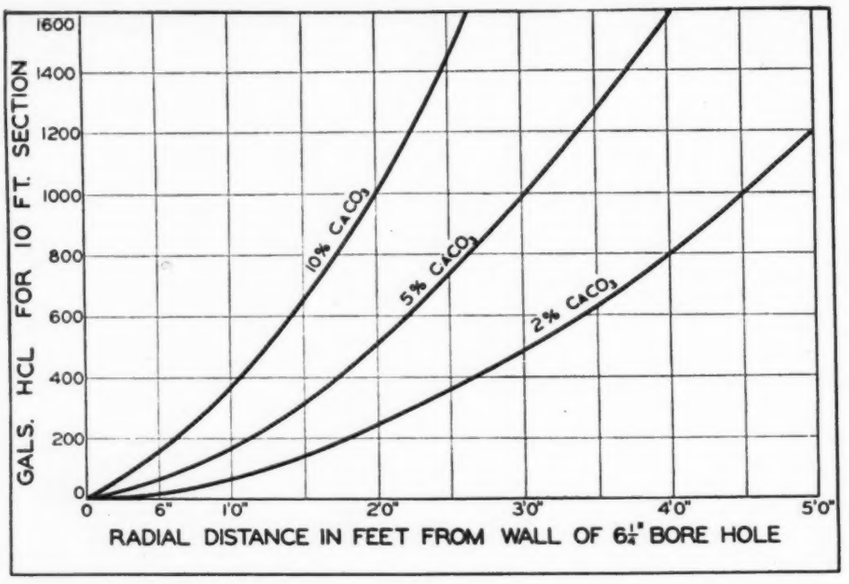

Fig. 5. Curves showing the amount of 15 percent hydrochloric acid required to remove varying amounts of calcium carbonate from a formation 10 ft. thick

divergence between calculated and actual productivities has also been observed by Core Laboratories Incorporated,[18] but not to the extent that was observed by Sherborne. In the Core Laboratories work corrections were made for the difference between true liquid permeability and that obtained by laboratory measurements with low-pressure air,[19,20] and for free gas in the formation, whereas Sherborne points out that these corrections were not made in his work. A number of reasons are advanced for this difference between actual and calculated productivities, chief of which are bubble resistance, interstitial water in the sand, and invasion of mud particles or water in the sand.[6,7,12] Mud acid can assist in removing the two latter mentioned causes of reduced productivities in wells by dissolving mud or clay in the formation and releasing invaded water and much of the interstitial water. Also, lower pressure differentials resulting from increased productivity by acid treating would tend to reduce any troubles from bubble resistance.

Favorable Well Conditions

The experience gained from two years of continuous treatment of sand wells with mud acid,[1] and much laboratory research work, has given some idea of the well conditions that should be looked for when selecting a well for a mud acid treatment. Proper solubilities of the formation to be treated, in mud acid and hydrochloric acid, are prime prerequisites for a mud acid treatment. These solubility prerequisites are:

1. At least a 10 percent spread between the solubility in mud acid and hydrochloric acid of the formation to be treated.

2. An average solubility in hydrochloric acid of less than 20 percent throughout the producing sand section. If only a few samples from a section show 20 percent or more solubility in hydrochloric acid, and the majority of the samples show less than this amount, the formation will be satisfactory for a mud acid treatment.

Oftentimes it is not possible to obtain formation samples from wells for solubility analyses, and, in these cases, the solubilities of similar sands in the same area or the solubilities of correlating sands in other areas must be relied upon.

If the solubility conditions mentioned are satisfactory, the following well conditions are favorable to the successful treatment of a well with mud acid:

1. Injection wells, either water or gas. The percentage of failures of this type of well is very small. In most injection wells there is surface plugging at the face of the sand formation to some degree, which plugging material can be removed with mud acid.

2. Wells that have been drilled through the producing sand with rotary tools, especially in cases where a poor mud has been used, or where the well has been drilled some distance below the sand to be treated, without setting pipe.

3. Wells that showed indications of being good oil producers on a drill-stem test, but which failed to make good producers when completed.

4. Wells that produce small amounts of water at irregular intervals.

5. Wells in areas where increases in production have been obtained by under-reaming or other methods of enlarging the bore hole.

6. Wells that are completed by gun perforating through the casing or by setting screens or perforated liners.

7. Wells that have abnormally rapid or sudden declines in production.

8. Poor wells that have a good bottom-hole pressure, or wells having a good bottom-hole pressure that produce smaller quantities of oil than offset wells.

9. Wells that have evidence of "Gyp" or acid soluble scales on screens, liners, gas anchors, or tubing perforations.

10. Wells that have had their production reduced by cement jobs.

11. Wells that produce silt or mud.

12. Wells wherein mud or water has been lost into the producing formation during drilling or workover operations.

13. Wells producing from formations showing very low resistivities on the electric log.

Electrical logs will sometimes give information regarding whether a sand contains bentonitic material. The electrical logging companies have found that in the Gulf Coast and other areas where the oil-producing sand frequently contains appreciable amounts of bentonite, abnormally low resistivity readings are obtained opposite the bentonitic zones, whereas the non-bentonitic sections of the same oil-producing sand exhibit much higher resistivity values that are considered "normal" to the particular formation. Bentonitic zones have frequently been called silty, dirty, or colloidal, by various writers who recognize, however, that the silty, dirty, or colloidal nature of the sand is caused by bentonitic material. The Houston Geological Society, in their discussion of electrical logging,[14] points this out, as do Leonardon and McCann.[23]

In cases where it is found that sands showing low resistivities produce oil or gas, or where there is good reason to believe that a sand should produce in spite of the low restivities logged, there is a very good possibility that a mud acid treatment will produce good results.

Volumes of Acid Used

Calculations show that for a sand of 1-ft. thickness, which has a porosity of 20 percent and a bentonite content of 10 percent, it will require 70 gal. of mud acid to remove the bentonite with-

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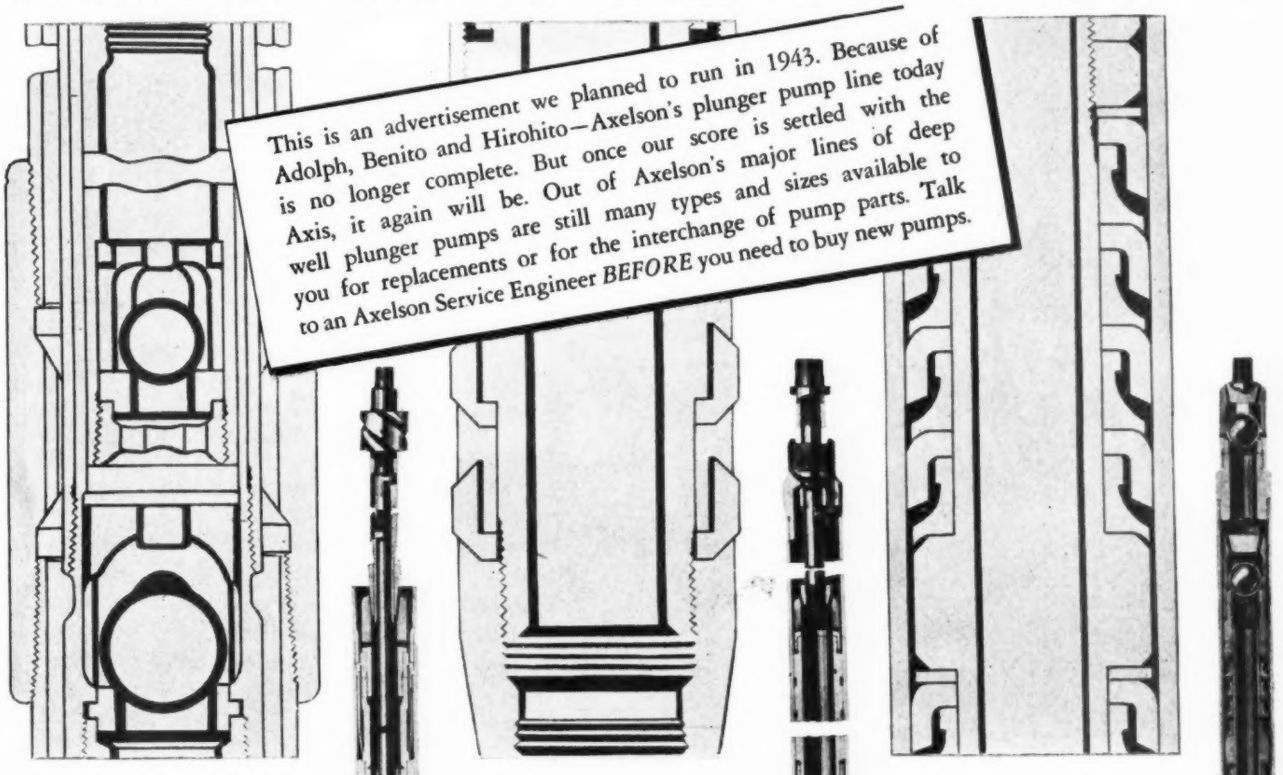

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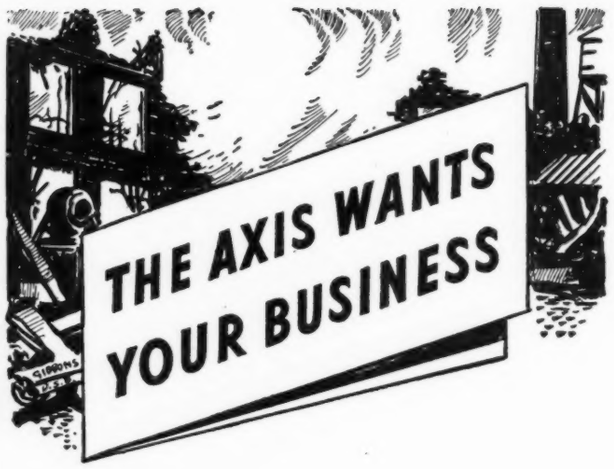

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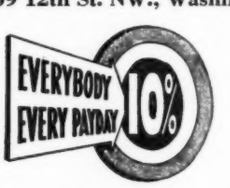

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in 6 in. of the bore hole, and 200 gal. of mud acid to remove the bentonite within 1 ft. of the bore hole. The curves in Figs. 3 and 4 show the amount of bentonite by weight within a given radial distance of the bore hole in a formation containing 10 percent bentonite; and the amount of mud acid required to dissolve the bentonite within a given radial distance.

The minimum acid gallonage recommended for the mud acid treatment of sand wells is 25 gal. of mud acid and 25 gal. of wash acid per ft. The average gallonage for the Gulf Coast is about 37 gal. of mud acid and 37 gal. of wash acid per ft. Larger gallonages of acid have given better increases in production, and there is every reason to believe that increased gallonages will give better results in nearly all cases. However, when gallonages of more than 200 gal. per ft. are used, the acid should be applied to the well in stages. Stage treating is a very good practice in any case, but the economics involved prevent the stage treatment of many wells.

In most of the treatments of sand wells in the Gulf Coast, equal volumes of Dowell mud acid and Dowell X wash acid are used. In cases where the solubility of the formation to be treated is 2-3 percent or less in 15 percent HCl, no wash acid is used ahead of the mud acid, but in cases where the 15 percent HCl solubility of the formation runs higher than 2-3 percent, it is recommended that the mud acid be preceded by an acid wash; the amount to be used depending upon the acid solubility of the formation. The purpose of the wash ahead of the mud acid is to remove any calcareous material from the zone in which the major portion of the bentonite solvent in the mud acid is spent. It appears that, in nearly every case, the bentonite solvent in mud acid will be spent within a radial distance of 1 ft. from the bore hole; and, in determining the amount of acid wash to be used ahead of the mud acid, it is necessary to calculate the amount of acid that will be required, theoretically, to remove the calcareous material in this 1-ft. zone. For example, in a formation having a solubility of 5 percent in 15 percent HCl, a volume of 18 gal. per ft. of sand exposed would be required. If the formation contained 10 percent calcareous material, a volume of 36 gal. per ft. would be required. The curve in Fig. 5 shows the amount of 15 percent HCl required to remove various percentages of calcium carbonate from a formation that has a porosity of 20 percent.

An acid wash solution should be used behind the mud acid in practically all cases, with the volume of wash being approximately the same as the volume of mud acid used. Any wash solution that follows the injection of mud acid into the formation should be flushed into the formation with a volume of oil or salt water that is at least equal to the volume of wash solution used, unless excessive pressures are encountered in pumping the oil or salt water into the formation. When fresh water or mud is used as the treating fluid, the wash solution should be followed only with enough fluid to clear the tubing.

Methods of Preparing Wells

More precautions should be taken in preparing a sand well for treatment than are ordinarily taken for the treatment of a lime well. The following preparations should be made on every well, whenever possible:

1. The operator should by some means determine whether the hole is clean and free of sand to a point below, or to the bottom of, the producing sand. This can be done by lowering the tubing to bottom, or if the tubing is open ended, a measuring line can be run through the tubing. If the well is found to be sanded up, it should be cleaned out before treatment. The presence of a loose sand in the bore hole of a well, extending to a point just above the top of the producing section, may decrease the productivity of a well to 5 or 10 percent of its normal value. There is practically no chance for a mud acid treatment to increase the production of a well that is sanded up.[2]

2. The operator should spot the tubing perforations or the bottom of open ended tubing below, or at the bottom of, the producing sand in order that the mud acid can be circulated upward past the face of the formation. This is not important where a gun-perforated section with no inside screen is being treated.

3. The operator should have readily available a sufficient amount of fluid to fill the well. The most desirable fluid to be used for treating is oil, the second choice is salt water, the third choice is mud (provided it is mud of a good quality) and the last choice is fresh water.

4. The operator should have the well equipped with high pressure wellhead equipment in cases where there is any possibility at all of the well requiring such pressures for treatment.

5. Prior to the treatment, the operator should make the proper arrangements for putting the well on production immediately after the treatment, in order that there will be no delay. Swabbing equipment is preferable to pumping or gas-lift equipment.

6. Any paraffin that may be present in the tubing should be cleaned out of the tubing before the treatment, as any paraffin that is pressured into the formation may damage the well.

Treating Technique

Most mud acid treatments are made in the conventional manner, using the Carr method of treating.[22] The Carr method of treating wells involves filling the well with fluid following which the chemicals are pumped down the tubing while bleeding off sufficient fluid at the casinghead to place the chemicals at the desired point in the well. As soon as this is done the casing valves are closed and the balance of the chemicals and flushing fluid are pumped into the tubing. In cases where the well will fill with fluid and the tubing perforations are set at the bottom of the producing section, what is termed the "soak procedure" is used when the first mud acid reaches the formation. In this case, sufficient mud acid to cover the screen or pay zone is spotted opposite the pay section and allowed to soak for 10 to 15 min. This is then bled up the hole and replaced by fresh acid, which is again allowed to soak for another 10 to 15 min. This second batch of mud acid is then bled up the hole, and the remaining mud acid and wash is pressured into the formation. When the hole will not fill, or when the tubing perforations are above the pay section, the soak procedure is not used, neither is it used when a well is completed with gun perforations and has no inside screen set.

When the formation temperature is 130°F., or more, the mud acid being squeezed into the formation should be pumped at such a rate that a period of at least 30 min. is required for the process. In cases when the formation temperature is less than 130°F., the total pumping time for the mud acid should not be less than one hour. Whenever possible, the mud acid being injected into the formation should be pumped continuously at such a rate that the minimum recommended injection time is observed or not exceeded. In some cases it is not possible to pump continuously at the required slow rate, due to the high injection pressures, and, in this case, it is necessary to pump intermittently. The wash acid can be squeezed into the formation at a faster rate than that required for the mud acid; however, the minimum time for injection of the wash solution into the formation should be at least 15 min.

Wells treated with mud acid should be placed on production as soon as possible after the treatment. If the operator can get the well on production within 30 min. after treatment, so much the better. Delays of a day or more may be detrimental.

(Continued on Page 98)

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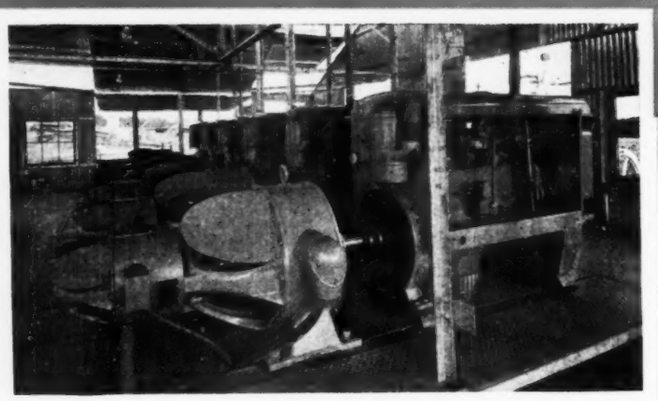

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(Continued from Page 95)

Results and Benefits

At the present time it is not possible to accurately predict whether a particular sand well will or will not respond to a mud acid treatment. This is due both to a lack of the necessary information concerning some wells and to an incomplete knowledge of the actual effects of mud acid in some formations. This situation is analogous to the position of the geologist in many cases. It can never be said definitely that oil will be found in a certain place. Only may it be said that the conditions for accumulation of oil are favorable. However, it can be said rather definitely in many cases that no oil will be found in certain areas. With mud acid it cannot be said definitely that a treatment will increase the production of a particular well. Only may it be said that the conditions favorable to such an increase are present. However, it can be said rather definitely in many cases that there is no chance at all for increasing the production of some wells by treating with mud acid. There has not been as large a percentage of successful treatments on sand wells with mud acid as there has been with limestone wells that are treated with hydrochloric acid; however, usually a larger percentage of what might be termed "Last Resort" wells are encountered in sand treating than in lime treating, which partly accounts for the lower percentage of successful treatments.

Many wells that are treated with mud acid are very slow to respond. Also, many wells do not show appreciable production increases for a week or so after treatment, and, in a few cases, the increase in production has not shown up for a month or more. Very often, wells that have been treated with mud acid will show a gradual and continuous increase in production for several weeks after treatment before they finally level off, and, as a general rule, wells that respond to mud acid treatment will hold their increases much better than lime wells that are treated with regular acid. Another noticeable result obtained with mud acid treating is that wells making only small percentages of water, although in some cases as high as 50 to 60 percent, generally show a higher percentage of increase in oil than water.

The primary purpose of the majority of acid treatments is, of course, to increase the current production of wells, or to put more barrels of oil into the tank for the operator. However, there are numerous other ways in which a mud acid treatment can be of benefit to the operator from a cost or profit standpoint that are not so clearly evident, but are none the less real. Such benefits are:

1. Reduction in lifting costs on wells by increasing the flowing life. In the case of a well that has gone dead, or is about to go dead, a mud acid treatment that will prolong the flowing life for a year or so, or even in some cases for a shorter time, will result in considerable saving to the operator. Three wells have been treated in the East Texas field to date for the purpose of keeping them flowing. One well was treated a year ago, another seven months ago, and the other six months ago. All of the wells are still flowing at this time.

2. In a gas drive field, or one under volumetric control, a mud acid treatment, or any method of decreasing the pressure drop or energy loss necessary to move the oil into the well, will result in an increase in the ultimate economic recovery of the well.

3. In a water-drive field, or one under hydraulic control, mud acid treatment of the sand will allow the operator to perforate a smaller section, higher above the water table. For example, an operator in completing a well, may decide to perforate enough of the section to give a well that will flow at a rate of 20 bbl. per hour on a ¼-in. choke. Suppose this requires that the top 10 ft. of a 20-ft. oil-producing section that is underlaid by water be perforated. This would mean that the bottom perforations would be 10 ft. above the water table and that a 10-ft. rise in the water table would cause the well to begin making water. On the other hand, if a mud acid treatment would result in a 100 percent increase in the productivity of any section that was perforated, the 20 bbl. per hour could be obtained by perforating only the top 5 ft. of sand, thus making the bottom perforations 15 ft. above the water table, and the water table could rise 5 ft. higher before the well began making water.

4. In a field where there is an expanding gas cap the same benefit from mud acid treatment could be obtained as was illustrated in the case of a water-drive field, except that it would allow the operator to perforate smaller sections, farther below the gas, and thus delay the time when the well would go to gas or have a gas-oil ratio that was too high.

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P 521.

A Review of Multiple-Zone Well Completions*

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Abstract

THIS paper presents representative data on multiple-zone completions that have been made in the several oil-producing regions of the United States. It is a joint effort of the Topical Committees on Drilling and Production Practice, and constitutes a progress report on the subject.

The desire of the oil industry to find ways and means of conserving steel in its drilling and production activities led to the decision to undertake this survey. An analysis of 89 multiple-zone completions indicates that an average per-well saving of 105 tons, or 46 percent, was realized in a multiple-zone completion, in comparison with two standard well completions.

Available information indicates that the initial completion of wells in more than one zone can be accomplished successfully. Reliable data on the effectiveness of the method are at present limited to the earlier stages of multiple-zone production. Sufficient representative data on the later life (especially during the artificial-lift period) of multiple-zone wells are not yet available to permit drawing any definite conclusions as to the ultimate overall practicability of the method.

Existing conditions with respect to critical materials reasonably may be expected to result in an accelerated development of improved technique and more advanced methods of application.

Introduction

At the spring meeting of the Southwestern District of the Institute's Division of Production, in Dallas, Texas, in February, 1942, a number of suggestions were advanced regarding ways and means of producing more oil with less use of critical materials, it having been agreed unanimously that for the duration of the war all projects undertaken by the committees of the Southwestern District should be in direct support of the war effort.

Prominent among these suggestions was a study of dual or multiple-zone completions; however, no decision was reached at that time as to the advisability of a paper on this subject. In the five months' period following the meeting a growing interest has been manifested in the subject due to the increasing scarcity of steel. In view of the wide interest exhibited, such a survey appeared to be warranted, inasmuch as the experience and data accumulated by operators having made multiple-zone completions were not available generally to the industry.

Subsequently it was decided that the Topical Committees on Drilling and Production Practice jointly would undertake a statistical survey of data on multiple-zone completion practices as a contribution to the petroleum industry. The two committees prepared a questionnaire, which was forwarded to all operators who have made multiple-zone completions. The executed questionnaires, which were returned to the committees, supplied the basic data used in this paper, which is to be considered as a progress report.

It was not the purpose of this survey to investigate the merits of multiple-zone completions or to offer recommendations regarding general applicability of the method. Instead, the objective of the study was to present basic data made available to the committees mainly from the viewpoint of methods, equipment employed, the initial degree of success achieved, and difficulties experienced. It may well be that the desire or necessity to expend the minimum amount of critical material will lead to wider adoption of multiple-zone completions where the method can be employed successfully. Therefore, it is hoped that the data presented herein may be of some assistance as a guide to operators electing to make multiple-zone completions who have not had previous experience with the method.

Objectives

A multiple-zone completion is considered herein as a means whereby two or more separate oil- or gas-bearing formations are exploited simultaneously in the same well. Under normal conditions the reasons prompting completion of a well in more than one zone usually would be either:

1. Economic: Initial investment required is substantially less for a multiple-zone completion than the expenditure necessary for drilling separate wells to the individual zones.

2. Regulatory: Spacing, or other restrictions imposed by regulatory bodies governing the number of wells permitted in defined surface areas.

However, under conditions existing at present, an important new reason for giving consideration to multiple-zone completions is the necessity for conserving steel.

Presentation of Data

Executed questionnaires were received covering multiple-zone completion of 89 wells in several of the different oil-producing districts of the United States. Obviously, all wells in which multiple-zone completions have been made in these areas were not reported on, but it does appear that a reasonable cross-section was obtained, so that the data supplied should be representative and reliable.

Multiple-zone completions in California and Illinois are not included in the 89 wells previously referred to. Cory's‡ recent paper (given at the annual meeting of the Institute in November, 1941) appears adequately to have covered California practice; moreover, a relatively small number of questionnaires was received from California.

In Illinois the very large number of multiple-zone completions, together with the wide range in procedure, indicated that questionnaire compilation of data would not be feasible. Instead, Messrs. R. J. Sullivan, of The Carter Oil Company, and Marshall Joy, of Cities Service Oil Company, prepared a summary of Illinois practice, which will be included before final printing.†

The data contained in the questionnaires were studied, and Table 1, "Tabulation of Data on Multiple-Zone Completions," was prepared as the most effective means of presenting the information obtained. The tabulation is a compilation of all data submitted on multiple-zone completions in the Gulf Coast, East Texas, West Texas, Oklahoma-Kansas, and Arkansas-North Louisiana areas.

Table 2 was prepared in order to highlight the more important features of Table 1.

From Table 2 it will be observed that of the 89 dual completions, 63 set casings through both zones and 26 set casing between zones. Sixty-nine of the wells used unloading valves of the Lewis and Otis variety. Only five were equipped with screen, and these opposite the lower zone. Two zones are being gas-lifted, and seven pumped. Packers have been classified as removable and non-removable, of which we have 65 and 24, respectively. It is interesting to note that 50 wells were com-

*Presented before American Petroleum Institute, Annual Meeting, Chicago, Illinois, November 9-13, 1942.

‡"A Review of Multiple-Zone Production in California," Robert F. Cory. *Proceedings A.P.I.* 22 [IV] 14 *(Production Bulletin No. 228)* (1941).

†This summary has now been completed and is presented as an "Appendix" at the end of this paper.

TABLE I. Tabulation of data on multiple-zone completions

Field	Number of wells	Date completed	Reason for multiple-zone completion	Average depth, (feet)	Interval between zones (1) and (2) (feet)	Type of formation of zones (1)	Type of formation of zones (2)	Casing size (oil string), (inches)	Point at which casing was set	Tubing size, (inches)	Screen	Type of packer used	Type of unloading valve	Daily rates of production zones (1)	Daily rates of production zones (2)	Producing	Production method zones (1)	Production method zones (2)	Savings—dual well compared to two single wells: Steel, Percent	Savings—dual well compared to two single wells: Steel, Tons	Savings—dual well compared to two single wells: Cost (percent)
Gulf Coast Area—																					
Texas:																					
La Gloria	10*	Early 1941	Planned cycling program	6,500	600	Sand	Sand	7	Through both zones	4½ and 1¼	None	Removable	Lewis	10,000 MCF	6,500 MCF	Simultaneously	Natural flow	Natural flow	42	132	32
Stratton	17	Early 1941	Planned cycling program	6,500	20	Sand	Sand	7	Through both zones	4½ and 1¼	None	Removable	Lewis	5,000 MCF	5,000 MCF	Simultaneously	Natural flow	Natural flow	42	132	32
Katy	3	7/42	Scarcity of material	7,400	100	Sand	Sand	7	Between zones	2½	Lower zone	2 non-removable 1 removable	Otis	20,000 MCF	10,000 MCF	Simultaneously	Natural flow	Natural flow	30	62	25
La Rosa	1	4/41	Obtain fuel gas	5,800	200	Sand	Sand	7	Through both zones	2½ and 1¼	None	Non-removable	Use 1¼-in. tubing	3,000 MCF	3,000 MCF	Simultaneously	Natural flow	Natural flow	24	28	40
Dickinson	1	1/42	Obtain additional source gas	8,000	50	Sand	Sand	7	Through both zones	2½	None	Non-removable	Otis	2,500 MCF	1,500 MCF	Simultaneously	Natural flow	Natural flow	49	193	38
Naubro	1	10/41	Economy	5,200	60	Sand	Sand	7	Through both zones	2½	None	Non-removable	None	1,500 MCF	70 bbl. oil	Simultaneously	Natural flow	Natural flow	41	67	35
West Ranch	1	4/40	Economy	5,700	700	Sand	Sand	7	Through both zones	2½	None	Non-removable	Brown equalizing valve	700 MCF	50 bbl. oil	Simultaneously	Natural flow	Natural flow	30	49	40
Jackson County	2	1940-1941	Obtain fuel gas	5,200 5,900	50	Sand	Sand	5½	Between zones	2	Lower zone	Removable	None	800 MCF	40 bbl. oil	Simultaneously	Natural flow	Natural flow	50	71	45
Anahuac	1	9/35	Obtain fuel gas	7,000	300	Sand	Sand	7	Between zones	2½	Lower zone	Removable	None	.....	35 bbl. oil	Lower only	Natural flow	Natural flow	50	135	44
Port Neches	1	6/41	Gas for lease operations	3,500	1,400	Sand	Sand	5½	Through both zones	2	None	Removable	Otis	700 MCF	100 bbl. oil	Simultaneously	Natural flow	Natural flow	50	62	45
Odem	1	11/41	Economy	5,300	1,800	Sand	Sand	5½	Through both zones	2	None	Removable	Otis	.....	.....	Intermittently	Natural flow	Natural flow	.....	.....	.....
Louisiana:																					
Cheneyville	1†	8/38	Economy	6,000	75	Sand	Sand	8⅝	Through both zones	2½	None	Removable	Otis	100 bbl. oil	100 bbl. oil	Together	Gas lift	Gas lift	.....	.....	.....
Hackberry	1	6/42	Scarcity of material	9,200	200	Sand	Sand	7 and 5 liner	Through both zones	2½ and 2	None	Removable	Otis	75 bbl. oil	75 bbl. oil	Simultaneously	Natural flow	Natural flow	49	143	45
White Lake	1	4/42	Economy	6,500	450	Sand	Sand	5½	Through both zones	2	Lower zone	Non-removable	Otis	176 bbl. oil	187 bbl. oil	Simultaneously	Natural flow	Natural flow	48	93	45
Ville Platte	10‡	Early 1941	Offset obligations	8,900	150	Sand	Sand	6	Through both zones	2 and 2¼	None	Non-removable	Otis	40 bbl. oil	120 bbl. oil	Simultaneously	Natural flow	Natural flow	50	120	45
Ville Platte	2	6/42	Economy	10,000	1,150	Sand	Sand	6	Through both zones	2 and 2½	None	Non-removable	Otis	80 bbl. oil	100 bbl. oil	Simultaneously	Natural flow	Natural flow	46	142	45
Anse La Butte	1	2/42	Economy	6,000	100	Sand	Sand	5½	Through both zones	2	None	Non-removable	Otis	150 bbl. oil	165 bbl. oil	Simultaneously	Natural flow	Natural flow	50	78	47
East Texas Area—																					
Carthage	1	8/42	Economy	5,900	1,000	Sand	Sand	5½	Through both zones	2	None	Non-removable	Otis	2,400 MCF	1,000 MCF	Alternately	Natural flow	Natural flow	46	155	45
Chapel Hill	1°	Early 1942	Economy	8,000	2,300	Sand	Lime	5½	Through both zones	2	None	Non-removable	Otis	Shut in	74 bbl. oil	Lower only	Shut in	Natural flow	44	87	11
Chapel Hill	1	Early 1942	Economy	8,000	2,300	Sand	Lime	5½	Through both zones	2	None	Non-removable	Circulation joint	Shut in	74 bbl. oil	Lower only	Shut in	Natural flow	44	96	30
Chapel Hill	1	2/42	Economy	8,000	2,300	Sand	Lime	7	Through both zones	2½	None	Removable	None	5,000 MCF	74 bbl. oil	Simultaneously	Natural flow	Natural flow	15	29	40
Long Lake	4	1940	Economy and planned cycling program	5,300	20	Sand	Sand	7	Between zones	2½	None	Removable	None	6,000 MCF	45 bbl. oil	Simultaneously	Natural flow	Natural flow	50	133	.....
Long Lake	7	1940	Economy and planned cycling program	5,300	40	Sand	Sand	5½	Between zones 5 and 2 through both	2	None	Removable	Otis	6,000 MCF	45 bbl. oil	Simultaneously	Natural flow	Natural flow	52	95	48
Long Lake	7	1940-1942	Economy and planned cycling program	5,300	20	Sand	Sand	5½ (5); 7 (2)	Through both zones	2	None	Removable	Otis	4,000 MCF	10 to 10,000 MCF	Simultaneously	Natural flow	Natural flow	52	95	48
Cayuga	3	1941	Economy and planned cycling program	4,000	150	Sand	Sand	6⅝ (2); 5½ (1)	Between zones	2	None	Removable	Otis	8,000 MCF	50 bbl. oil	Simultaneously	Natural flow	Natural flow	50	52	48
West Texas Area—																					
Kimble County	1	7/42	Economy	1,500	150	Sand	Sand	8⅝ and 5 liner	Through both zones	2½	None	Removable	None	Shut in	4 bbl. oil	Lower only	Shut in	Natural flow	41	25	37
Kermit and Estes	2	Early 1941	Gas for artificial lift	2,500	200	Sand	Sand	7	Between zones Set through lower zone not cemented	2½ and 1½	None	Removable	None	250 MCF	4 bbl. oil	Simultaneously	Natural flow	Gas lift	48	48	48
Kansas-Oklahoma Area—																					
Ramsey	1	8/41	Offset obligation	4,800	200	Lime	Sand	5½	Between zones	2½	None	Removable	None	24 bbl. oil	15 bbl. oil; 288 bbl water	Simultaneously	Natural flow	Pumping	50	56	46
Gurney	1	5/41	Economy	3,150	175	Lime	Sand	7	Between zones	2½	None	Non-removable	None	32 bbl. oil	38 bbl. oil	Intermittently	Pumping	Pumping	50	60	46
Trapp	1	7/42	Increase in allowable	3,300	200	Lime	Lime	7	Between zones	3	None	Non-removable	None	155 bbl. oil 3 days	140 bbl. oil 15 days	Intermittently	Pumping	Pumping	47	39	42
Anschutz	1	4/41	Offset obligation	3,300	250	Lime	Lime	7	Between zones	2	None	Non-removable	None	36 bbl. oil	32 bbl. oil 33 bbl. water	Intermittently	Pumping	Pumping	50	56	46
Arkansas-North Louisiana Area—																					
Rodessa	1	12/36	Obtain gas for fuel	6,000	150	Lime	Lime	7	Through both zones	2½	None	Removable	Otis	2,000 MCF	225 bbl. oil	Simultaneously	Natural flow	Natural flow	50	144	46
Shuler	1	5/42	Test feasibility of dual completion	6,800	120	Sand	Sand	7	Through both zones	2½	None	Non-removable	None	100 bbl. oil	2,000 MCF	Simultaneously	Natural flow	Natural flow	50	.....	50

*Three of these wells used for injection purposes. Volumes as high as 20,000 MCF for each zone returned to formation.

†Well produced zones individually on natural flow, but combined when natural flow ceased and placed on gas lift.

‡Much difficulty experienced in effecting dual completion. Eight attempts to set various packers had been made before successful seal was obtained.

°Several of these wells at one time were or now are being used as gas-injection wells in a pressure-maintenance project. The lower zone in one of the wells is being produced by gas lift through a string of 1½-in. tubing at 4350 ft. inside of 2½-in. tubing.

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Several of these wells at one time were or now are being used as gas-injection wells in a pressure-maintenance project. The lower zone in one of the wells is being produced by gas lift through a string of 1½-in. tubing at 4350 ft. inside of 2½-in. tubing.

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pleted with 7-in., 24 wells with 5½-in., 12 wells with 6-in., 2 wells with 6⅝-in., and 1 well with 8⅝-in. casing. The smaller casing sizes appeared to offer no obstacle to dual completions.

As previously stated, Cory's paper is considered to be adequate for a review of California multiple-zone practice, and is more comprehensive than any analysis that might be offered herein. In summary, Cory states that the trend in California is away from multiple-zone completions, and the present feeling is that it should be used only in special cases justified by local expediency. This conclusion would appear to be based on difficulties experienced in producing multiple-zone wells during both flowing and artificial-lift periods. The questionnaires received from California appear to substantiate Cory's conclusions quite well. It is indicated that most of the multiple-zone wells now are producing from one zone only, even though the original completion was in two or three zones. The opinion is expressed by California operators that multiple-zone completions there might result in reduced ultimate recoveries per zone as compared to single-zone completions.

It is recognized that operating conditions as related to multiple-zone completions differ greatly between California and the Mid-Continent areas. Inability to put the two areas on a comparable basis is indicated by: (1) differences in rules issued by state regulatory bodies governing completion practices; (2) wide variance in proration plans, especially with regard to potential ratings; and, (3) non-uniformity in production reservoir characteristics such as nature and thickness of producing zone sections, viscosities of oils, etc.

The principal reason for multiple-zone completions as refleceted in the Mid-Continent questionnaires was economy. The economies effected have been in the nature of reduced drilling costs, savings in casing and tubing, drilling equipment, lease roads, flow lines, dredging canals, derricks, pumping units, etc. In most instances the standard casing program was found to be about the same as that selected for the dual completion.

From the questionnaires it was observed that, in many of the wells, squeeze cementing was resorted to before attempting to complete in more than one zone. There were 17 cases reported of squeeze cementing between zones, 5 above the top zone, and 8 opposite or below the lower zone. It is obvious that the purpose of the 17 squeeze jobs between zones was to insure a complete shutoff between them, whereas the other 13 squeeze jobs may have been performed to shut off gas or water. Some difficulties have been experienced with sand-cutting the tubing opposite the upper zone. Most of the operators now are attempting to overcome this trouble by covering the portion of the tubing opposite the upper zone with a rubber or neoprene sleeve, although some have installed as a substitute a pipe sleeve over the tubing.

Generally, no serious difficulties were experienced in making the initial multiple-zone completions. Most of the troubles reported were with packer settings, and these apparently were of a temporary nature, with final successful results. No evidence was submitted which would indicate commingling of zones due to leakage around the packer after it had been set.

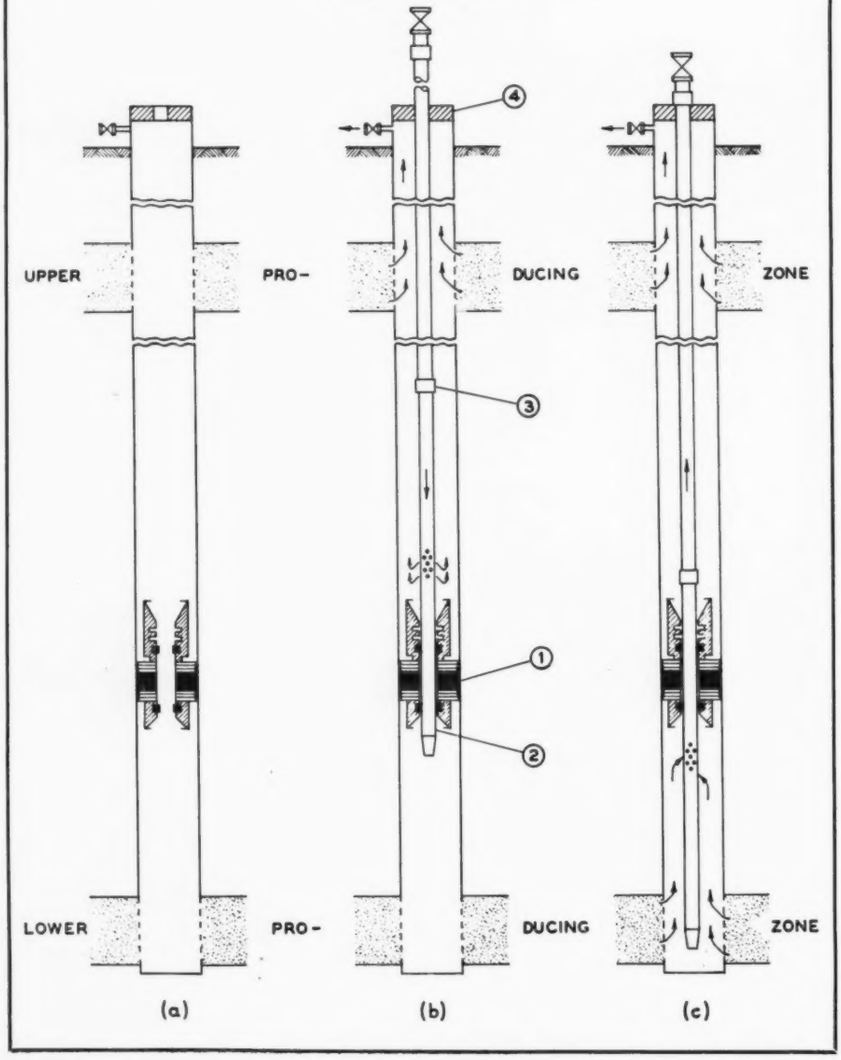
The more commonly reported difficulties in completing and producing multiple-zone wells are as follows:

1. Sand-cutting the tubing opposite the upper zone, resulting in commingling.
2. Difficulty in setting packers.
3. Some instances of stuck packers.
4. Cases of trouble in pulling or seating bottom-hole choke; also in swabbing the well in, both due to sand plugging the side-door choke.
5. Few cases of producing both zones through the tubing in order to prevent paraffin deposition in annulus.

Attention is directed to the fact that, of the 89 multiple-zone wells studied, only 9 zones in total were being produced by artificial lift, 2 by gas lift, and 7 by pumping.

The seven zones being pumped are in wells in the Oklahoma-Kansas area. Present practice is intermittent production of each zone separately, by pumping through the tubing. During the first 15 days, the month's allowable may be pumped from the lower zone, after which the tubing is raised enough to bring the perforations in the tubing above the packer; then the allowable for the upper zone is pumped the latter

Fig. 1. Typical dual well completion method using non-removable type packer. (1) Non-removable type packer. (2) Tail pipe. (3) Safety joint. (4) Christmas tree



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half of the month. Up to date this practice has been entirely satisfactory.

The questionnaires contained a request for the operators' plans regarding artificial lift. Thus far most of the operators do not seem to have planned a program as to the manner in which artificial lift will be applied to the individual zones when this stage of production becomes necessary. A few seem to feel that pressures in the two zones will be equalized sufficiently by the time artificial lift is necessary to permit the zones to be produced together as one operation. Others offer the opinion that the zones may have to be produced artificially one at a time and separately, say the lower first and the upper one later. Still others comment that both zones will be separately and simultaneously lifted artificially; for example, by gas-lifting the upper zone by means of a macaroni string in the annulus, and by pumping the lower zone through the tubing.

Methods and Equipment

On account of wide common usage, the term "multiple-zone completion" has been used throughout this paper. Actually, however, all 89 of the wells included in the study were completed in only 2 zones; hence, they might more properly be termed "dual completions."

The increasing use of the multiple-zone completion method has resulted in the development of different techniques and the availability of various kinds of equipment. In the normal course of a multiple-zone completion there are but two major items of equipment which usually would not be used in a single-zone well. These two pieces of equipment, of course, are the packer set between the two producing zones, and the unloading valve. A description briefly outlining several typical dual-completion methods, with emphasis on the purpose and type of special equipment such as packers and unloading valves, is given hereinafter.

It will be appreciated that the methods and equipment described are not to be construed as recommendations of the authors, but simply as a means of illustrating some of the various methods followed and equipment utilized. It is hardly necessary to point out that conditions existing in an individual well, together with the particular purpose of the dual completion to be made and the operator's judgment, will be the determining influence on choice of method and equipment.

TABLE 3
Summary tabulation

Area	Number of multiple-zone completions	Average per-well savings of dual completion compared to two single wells		
		Steel:		Cost (percent)
		Percent	Tons	
Gulf Coast	55	45	116	34*
East Texas	25	48	93	41†
West Texas	3	47	41	47
Kansas-Oklahoma	4	49	53	46
Arkansas-North Louisiana	2	50	157	48
		Weighted average per-well savings:		
Total wells	89	46	105	37

*Based on 41 out of 55 wells.
†Based on 19 wells out of 25. Dual completion of one of the 19 wells cost considerably more than the estimated cost of drilling 2 wells, on account of protracted fishing job resulting from difficulties with packer setting.

Dual Completions Using Non-Removable Packer

General. This method, shown in Fig. 1, is the simplest type of dual completion. The lower zone may be screened as shown in Fig. 2, if desired. A side-door choke or similar upper inlet (unloading) valve also may be used in conjunction with this method. It is assumed that both zones have been suitably perforated and treated, tested, or otherwise prepared for completion.

Operation No. 1: Fig. 1(a). This operation consists of running and setting the permanent-type packer at the desired position in the well.

Operation No. 2: Fig. 1(b). The tubing with the tail pipe, which is finally to seal off in the packer body, is run into the well until the anchor pipe is through the packer at about its final position. The tubing then is raised sufficiently to place the tail-pipe perforations above the packer. The upper zone then is washed or swabbed into production.

Operation No. 3: Fig. 1(c). The tubing now is lowered sufficiently to place the perforations below the packer, and tubing hung on the tubing head. The lower zone then is swabbed into production.

General. Fig. 2 shows another kind of typical dual completion, illustrating the use of a permanent- (non-removable) type packer with a screen setting in the lower zone. An Otis side-door choke is shown as one type of unloading valve. The operation is unchanged in cases in which the screen is not used [Fig. 2(a)], and the lower screen and packer [Fig. 2(b) to (f)] merely being eliminated. Various makes of packers and other accessories are available for this type of completion. It is assumed that both zones have been suitably perforated and treated, tested, or otherwise prepared for completion.

Operation No. 1: Fig. 2(a). The screen and liner are run into the hole on drill pipe or tubing, a partial washing job made by spotting a safe amount of water, the screen and liner released, the liner packer collapsed, and the drill pipe removed.

Operation No. 2: Fig. 2(b). The permanent interzone packer then is run in on tubing or drill pipe, the mud above the packer is conditioned, and the packer is set in the desired position. The tubing or drill pipe and setting tool then are removed.

Operation No. 3: Fig. 2(c). Tubing then is run back into the hole with the tail pipe, inner packoff, safety joint,

TABLE 2
Miscellaneous summary

Type of completion: Upper zone / Lower zone	Number of wells	Casing through both zones: size	Casing through both zones: inches	Casing between zones: size	Casing between zones: inches	Removable packers	Non-removable packers	Number of Unloading valves	Number of screens	Number of gas-lift zones	Number of pumping zones
Gas and gas	40	31	7	3	7	35	5	39	1	0	0
		6	5½								
Gas and oil	28	4	7	7	7	24	4	14	3	1	0
		6	5½	9	5½						
				2	6⅝						
Oil and gas	1	1	7	..	..	0	1	0	0	..	0
Oil and oil	17	1	8⅝	4	7	3	14	13	1	1	7
		9	6	1	5½						
		2	5½								
Gas and oil (input)	3	3	6	..	..	3	0	3	0	0	0
Total	89	63		26		65	24	69	5	2	7

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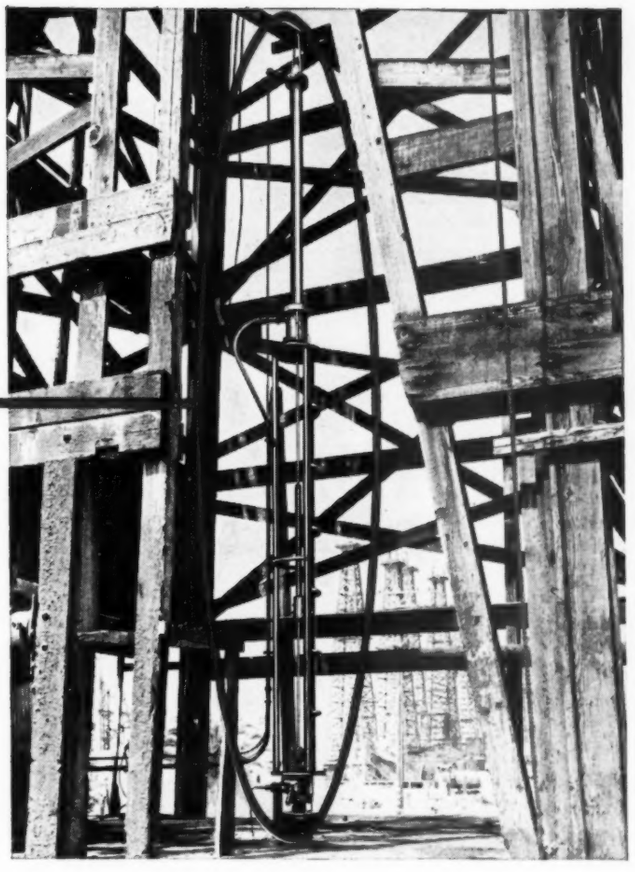

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and side-door choke, or equivalent material, assembled as shown in Fig. 2(c). The tubing seat is located, and the tubing-hanger nipple inserted at the correct spacing for hanging. The tubing packer then is lowered to a point close to its final setting point, and washing is started and continued until the well flows through the annulus.

Operation No. 4: Fig. 2(d). Circulation is stopped, the tubing packer is set and locked, and the tubing hung.

Operation No. 5: Fig. 2(e). If the well stops flowing through casing, oil or gas may be circulated through the side-door choke until the well is flowing again. Circulation is stopped, and the well flows or may be swabbed in through the tubing until strong flow is established.

Operation No. 6: Fig. 2(f). When both tubing and casing are flowing sufficiently, the tubing is closed in, and a blank bean run into the side-door choke. This separates the tubing flow from that in the annular space. Swabbing might be necessary to re-establish flow in the tubing, and this may be carried out in the usual manner until the well may be put on production.

Completion Using Lewis Valve

General. Fig. 3 shows a typical dual-completion method that is representative of a number of successful installations, using a removable-type packer and the Lewis unloading valve. This latter device was developed for special application to gas-distillate wells for the purpose of removing condensate from the annulus. In wells in which this device has been used, the casing string has been 7 in. with a 4½-in. tubing string as the intermediate string and 1¼-in. tubing as the macaroni inner string. As in other illustrations, the well is assumed to be suitably prepared for completion.

Operation No. 1: Fig. 3(a). The tail pipe, packer, Lewis valve, and 4-in. tubing are assembled and run into the hole. The packer is set at the desired point, and the 4½-in. tubing landed in the tubinghead. The well may be washed in partly, prior to setting the packer.

Operation No. 2: Fig. 3(b) and (c). The macaroni string next is run, connected into the Lewis valve and hung in the tubing head. The actuating cylinder then is assembled ready for operation. The well next is washed in, down the 1¼-in. tubing; and, by means of operating the Lewis valve, through either the upper-zone-producing annulus or the lower-zone-producing annulus, as shown in Fig. 3(b) and (c).

Operation No. 3: Fig. 3(d) and (e). After the two zones have been washed in, the well is placed on production through the two annular spaces. In the event of difficulty in inducing natural flow, the inner macaroni string may be used to assist by jetting gas down the string and into the desired annular space. The routine use of the macaroni string is for the purpose of continuously removing liquid that accumulates at the bottom of the well. The operation of the Lewis valve is controlled automatically by means of a timing device at the surface, and power for raising and lowering the tubing at set intervals is obtained from one of the annular producing passages.

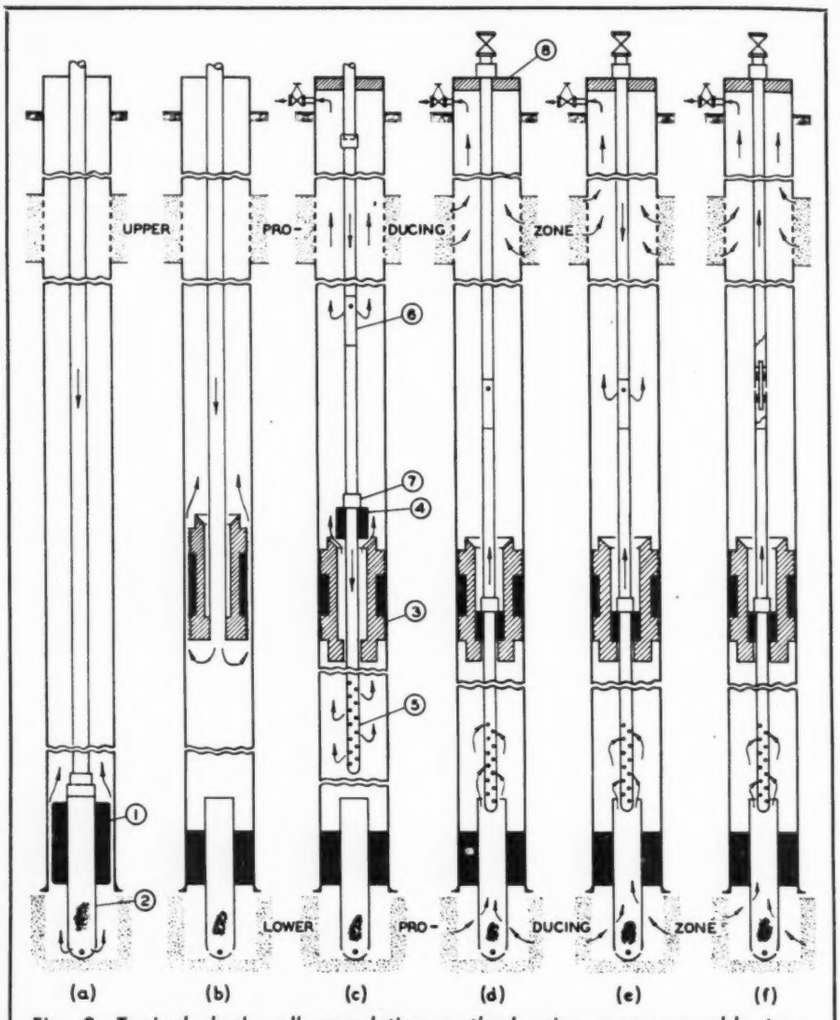

Fig. 2. Typical dual well completion method using non-removable type packer. (1) Screen collapsible packer. (2) Screen. (3) Non-removable type packer. (4) Tubing packer. (5) Tail pipe. (6) Side-door choke. (7) Safety joint—left-hand thread. (8) Christmas tree

Summary

As stated in the introduction, one of the main objectives of the survey was to examine multiple-zone completions already made from the point of view of savings of critical materials by means of this method of completion. In Table 1, savings in steel and cost realized by individual multiple-zone wells were shown, and these figures are summarized in Table 3.

Table 3 illustrates by areas the average savings in steel and money on a comparable basis with two standard wells. It is indicated that the weighted-average saving for the 89 cases studied is 46 percent, or 105 tons of steel, and a reduction of 37 percent in initial drilling cost for a multiple-zone completion as compared to two single-zone wells.

The 89 wells listed in Table 1 include not only initial multiple-zone completions, but a number of original single-zone wells that later were converted to dual producers. Serious difficulties in such cases of conversion were not reported, and this application of the method offers possibilities if there are a number of producing zones cased off.

The various procedures followed and different kinds of equipment used were described in the questionnaires. However, no attempt has been made in this paper to describe all the alternative methods or equipment employed. In-

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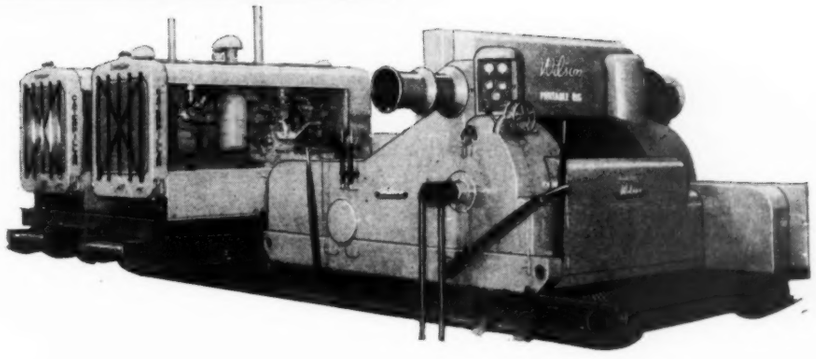

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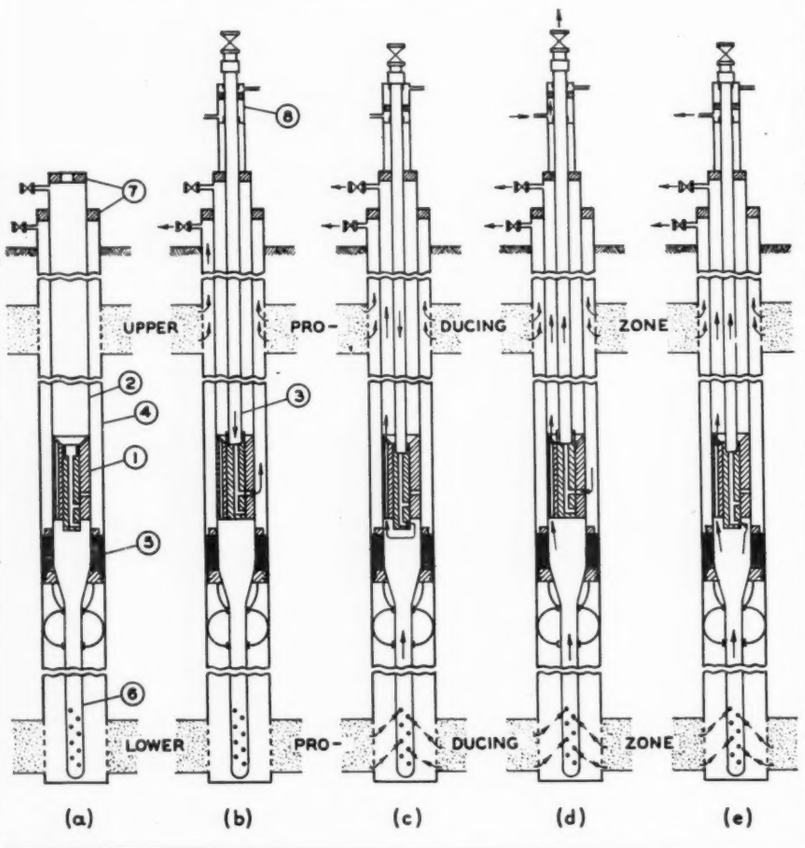
stead, generalization was attempted in order to present an overall picture of the essentials involved, realizing that local conditions and operators' choice would dictate the final selection of both methods and equipment. Selection of type of packer, point of packer setting, type and placement of unloading valve, screen setting, casing point, etc., are flexible, and rest upon requirements of the individual well concerned and the judgment of the operator.

The questionnaires requested data on problems encountered in operating multiple-zone wells after completion had been made, and the manner in which such difficulties were overcome. Cases of trouble due to sanding up as a result of sand-cutting the tubing opposite the upper perforations and paraffin difficulties were reported but, on the whole, no really major problems in producing multiple-zone wells were brought out. This may be explained partly by the fact that most of the completions are of fairly recent date, and are being produced at low allowable rates on natural flow. Perhaps during the later producing life of such wells, when water is being produced and other difficulties such as sand entering the hole become more common, the more unfavorable aspects of producing multiple-zone wells will appear.

It was hoped at the outset that it would be possible to present some reliable data on artificial-lift experience in multiple-zone wells. However, only in California and Kansas has any experience in artificial lift been accumulated. As discussed previously, California operators report considerable difficulty in artificially lifting their multiple-zone wells. On the other hand, under conditions prevailing in the Kansas wells on which data were obtained, artificial lift appears to constitute no operating difficulty. The contrasting experience in these two areas would seem to indicate that local conditions may be the governing factor in artificially lifting multiple-zone wells.

Included in the questionnaire was a request for the operators' opinion regarding whether operating cost would be greater or less for multiple-zone completions. Numerous operators reported that, in their opinion, it would be less costly to operate a well completed in two zones as compared to operating two individual wells; whereas others were directly opposed to this view, on the ground that the well would require more servicing and supervision when producing from more than one zone. Because of the widely divergent answers to the question of operating cost, it appears that operators are not as yet in a position to support any conclusion on this point.

Fig. 3. Typical dual well completion method using Lewis valve. (1) Lewis valve. (2) Tubing. (3) Macaroni tubing. (4) Casing. (5) Removable packer. (6) Tail pipe. (7) Christmas tree. (8) Actuating cylinder for Lewis valve. Note: Automatic timer is used to operate cylinder (8), which raises and lowers the macaroni tubing



Conclusion

It will have been recognized by now that this paper is substantially a progress report of experience on multiple-zone practice accumulated by the industry to date. It is apparent that, for the most part, reliable data at present are limited to the earlier stages of multiple-zone production. Sufficient representative data on the later life of multiple-zone wells (especially during the period of artificial lift) are not as yet available to permit drawing definite conclusions as to the ultimate overall practicability of the method. Nevertheless, on the basis of the data submitted and analyzed, it would appear possible to arrive at some general conclusions. These conclusions are outlined as follows:

1. It is indicated that the initial completion of wells in more than one producing zone can be accomplished successfully. Initial multiple completion may be expected to result in a saving of about 45 percent in steel consumption and approximately 40 percent in drilling costs, as compared to the drilling of two standard wells.

2. It does not follow that a successful initial multiple-zone completion ultimately will yield as satisfactory results as would single wells to the individual zones. Generally speaking, it is felt that this type of completion offers promise of being entirely satisfactory under conditions where consolidated productive formations exist and where final fluid volumes handled will come within limits of the permanent equipment in the well. On the other hand, when serious operating problems could be anticipated as a result of multiple completion, then the practicability of the method certainly would be questionable. For instance, if sand conditions necessitated screening of both zones, or if frequent workover jobs were required, the overall result of a multiple completion might be distinctly unfavorable.

3. Insufficient data on account of limited experience under the different conditions existing preclude any firm conclusions regarding the application of artificial lift in multiple-zone wells.

4. It is indicated that the average operating costs for multiple-zone wells probably will be greater than for stand-

ard completions. This opinion is based on: 1, operation of the well will be more difficult, especially during artificial lift; and, 2, repair and work-over operations will be more complicated. Perhaps the lower initial well investment, together with benefits accruing as a result of undeferred production, would offset increased production costs.

Finally, it can be said, in spite of the uncertainties involved, that the necessity under existing conditions to produce the most oil with the smallest amount of steel expenditure encourages consideration of multiple-zone completions. Most of the problems in connection with the method appear to be mechanical ones. In this early stage of its development, the practice already has commanded the attention of both operators and manufacturers. The present situation concerning critical materials reasonably may be expected to result in an accelerated development of improved equipment and more advanced methods of application.

Acknowledgment

The authors wish to express their appreciation for the assistance of the membership of all topical committees on drilling and production practice in accumulating the data which were the basis for this paper.

Grateful acknowledgment is extended to all the operators who prepared questionnaires, without which active coöperation the study would not have been possible.

Especial thanks are due R. E. Bridges, of Humble Oil and Refining Company, and to W. S. Crake, Shell Oil Company, Inc., who worked with the authors in compiling and studying the data contained in the questionnaires.

Appendix

The general report of which this is to be a part was conceived as a contribution by the Institute's committees, looking toward the encouragement of steel conservation in the drilling of oil wells. Multiple zone well completions have for the last five years received a good deal of attention in the Eastern District, particularly in the Illinois Basin. From the beginning of the Basin Area's intensive modern exploration and development campaign in 1938, the practice of producing more than one formation through the same casing string has grown to become one of quite widespread use and manifold variations. This growth took place so rapidly that the multiple zone well had been regarded as commonplace for some time before the second World War focused the efforts of all oil operators upon the problem of husbanding materials. Since 1939 the Eastern District Production Practice Committee has made several reports on the subject finally culminating in sponsorship of a paper entitled, "Casing Window Practices in the Illinois Basin," which was presented at the American Petroleum Institute's Tulsa, Oklahoma, Mid-Year Meeting on May 21, 1941.

Rather than burden this discussion with a repetitious review of the methods already described in that published form, let it be said merely that since a year ago window practices and other methods of exposing a plurality of pay formations in one hole are more widely employed than ever. Until special alloy pipe, constructed mainly of aluminum or magnesium, became critically scarce, that system of making windows in oil strings was the preference of nearly every operator confronted with the problem of simultaneously producing sand zones of a type requiring nitroglycerine shots for satisfactory completion, and at the same time of protecting the intervening hole with a cemented casing. We intend now to discuss only the more recent advancements in multiple zone development (most of which have arisen from the scarcity of metals) along with the more important variations of simple gun-perforation or ripping.

Windows

1. **Removable pipe.** As the most direct substitute for aluminum and magnesium alloys, unusually soft or unusually thin sections of steel pipe are placed in the string opposite any upper horizon that is to be later exposed by reaming and then shot with nitroglycerine. The procedure, of course, is identical with that followed in the application of non-ferrous alloys for the same purpose. Briefly, this consists of making an open hole well completion in the lowermost sand, then bridging the pipe just under the window, removing the window material itself and the cement behind it with an expanding rotary cable-tool reamer, shooting the face thus exposed, and cleaning out all tamps, bridges, and cavings down to the total depth before installing tubing. The pipe ends at the top and bottom of the window are protected by special shoes designed for the service. A typical thin-walled, soft pipe of the sort described has a wall thickness of from 0.13 in. to 0.20 in., with a yield point seldom exceeding 30,000 lb. per sq. in. Of course, it is intended to serve only as a temporary connector until after cement has had an opportunity to set in wells seldom exceeding 3000 ft. in depth. It can be removed at rotary tool cutting rates in the neighborhood of 5 to 8 ft. per hour and at cable tool rates of about 2 ft. per hour.

2. **Milling.** First adopted to accommodate older wells where steel pipe had been set on a lower sand, but more lately utilized because of the scarcity of all tubular goods, the outright milling of windows through conventional steel oil strings is another method finding equal favor with the "light steel" method. As described in last year's casing window paper already mentioned, hydraulically operated rotary reaming tools, fitted with especially hard-faced knives, are used to make a casing cut, after which the window length is milled to the desired point. Generally speaking, the rate of removal approximates 1 ft. per hour, including cement. Similar work has been done with expanding cable tools of the under-digger type, but rates are much slower and the action is of course not nearly so positive. Greatest difficulty occurs in obtaining a surface for cable-tool cutters to work upon. Despite the fact that outright milling of windows in oil strings is the most expensive means, it remains one of the most popular because it shares with the "light steel" method the apparent advantage of permitting sounder cement jobs. Estimates of the number of windows thus made are difficult to obtain, but it is safe to assert that they amount to several hundred.

3. **Liners.** The term "liner" in this instance is almost a misnomer, as actually the oil string is run in two or more sections, beginning with a short string cemented through drill pipe or tubing and situated between the lowermost producing formation and the next lying above it. Windows are left by running a string of the same or greater diameter to the top of the formation that is to produce through the window and cementing it either to the next window or to the surface. A back-off tool, sometimes of the drillable sort, is used to run the so-called liner on either drill pipe or tubing so that it can be cemented in position by the displacement method. Operators have their individual preferences regarding matters such as swinging the section or seating it, depth of cleaning out excess cement, etc. One of the undesirable features involved is the difficulty of maintaining the entire open hole in good condition during what may well turn out to be a rather lengthy period of time. Needless to say, careful, competent mud control is essential, even though it does not constitute a problem offering insurmountable elements. The most hazardous aspect of the liner method is the fact that it depends upon displacement cementing and that failures are not as easily nor economically repaired by squeezing, as ordinarily. In choosing a method of leaving windows, the operator's judgment is commonly governed by the length of the pipe section that must be displacement cemented, along with the occurrence and location of water sands

in their relation to the pays being developed.

4. **Casing J-tool.** More economical than the drill pipe or tubing method of cementing pipe sections below and between windows is a more recently evolved but not yet general means of running and cementing pipe sections on the casing itself. This depends essentially upon a letting-in tool of the J-slot type. In effect, the method amounts to a two-stage means of cementing the oil string and of separating the string during the cementing operation so as to leave a window opposite the upper sand. An Illinois pattern shoe of the kind used in conjunction with alloy metal windows is fitted with J-slots on either side, reinforced with an outer shrink ring, and installed at the upper end of the lower pipe section. Its empty end, wherein the slots are cut, is converted to a slip-joint that will accommodate a plain end casing joint bearing lugs that fit the slots. When the guide shoe has reached a casing seat shoulder left for the purpose, the entire string may be allowed to stand on the shoulder so that rotation frees the letting-in lugs and allows the upper end of the string to be picked up.

Cementing, it has been found, is best accomplished by pumping a comfortable excess of cement ahead of a plug in the first stage, stopping the plug on a conventional float collar below the J-tool, releasing the tool, conditioning the hole, and then pumping a second plug to within two joints of the upper section's end. Some operators regard the J-tool as less positive than other devices used with tubing or drill pipe, but it has thus far not failed in more than one of a dozen cases. It usually is considered as embodying better cementing technique, and under properly skilled supervision holds out no extreme difficulties. In the event of a failure to release, the continuous string can be cemented and the window may later be milled out down to the tool if necessary.

5. **Nitroglycerine windows.** Although not regarded in the light of first experience as very feasible, removal of casing opposite pay sands by creating windows with nitroglycerine has finally begun, since a year ago, to offer limited promise. Ordinarily, the window site is first heavily perforated with bullets before a charge of nitroglycerine is detonated against the producing sand behind. The use of heavy calibre mushroom bullets, as evidence shows, tends to allow the shot to exert its greatest effect in an outward direction. Such a shot must be very solidly anchored and tamped as well as heavily concentrated in order to leave the pipe ends in condition permitting re-entry into the window itself and then into the casing below.

Perforation

Where oil sands appear to be sufficiently permeable, perforation by either gun or casing ripper is, of course, quite commonly utilized. Likewise, where too many windows or other mechanical obstacles might constitute a hazard, perforation is generally relied upon. It is not often that any effort is made to prevent mingling of the production from a plurality of pay horizons in the same well bore. In most instances, they are near enough to one another that little is to be gained by separation of the production. Again, flowing life is so brief that sucker rod pumping must soon be resorted to and the impractical aspects of separating production in the well are such as to render separation highly inadvisable. There are times, nevertheless, when the lowermost pay is a sand or limestone so highly permeable and so heavily produced in the vicinity that there is not only fear but a certain amount of evidence that thiefing action occurs between pays. To guard against this danger, some operators have successfully undertaken the installation of a packer, equipped with a standing valve, between pays, or have otherwise so pumped their wells that a production packer will not permit the movement of fluid from one formation to the other. Somewhat fewer installations have been made to take flowing production from one formation while the other is pumped, but these have invariably been of a temporary nature not worthy of great mention.

The large scale repressuring projects in the Salem, Loudon, and New Harmony pools of the Illinois Basin contain numerous instances where gun perforation of multiple pays is employed to conduct high-pressure gas in separately controlled streams to oil sands. Single or multiple packer arrangements are necessary in such instances.

Conclusion

So many are the supplementary practices accompanying the chief multiple completion methods described that there is no way here of discussing them in significant detail. As would be expected, a great many centralizers, guides, and other cementing accessories are employed.

Multiple zone completions have, furthermore, become so commonplace in this territory that no accurate data can readily be assembled as to the number of wells thus finished. The Eastern District Committee memberships can only supply an informed estimate that applications must reach in the neighborhood of 1700 windows. Because of their early preponderance before the year 1942, alloy metal windows should account for more than 40 percent of the total, but, currently, the liner method seems to have the lead, closely followed by the systems of milling or running light steel connectors. There must be probably 2000 wells to date in which upper horizons are producing through gun perforations, although in many instances the wells already have windows exposing other sands. The ready acceptance of the multiple well over a relatively brief time is measure enough of the method's basic soundness and practical service ability. Failure frequency and production results have been good enough to accelerate progress consistently. Its plainly fortunate advancement prior to the war's emergency has brought the technique to a place where the multiple zone method of completing wells now stands as a most important factor in the industry's war-time operations. Reckoning, from past performance, it is not amiss to predict that improved developments of a related character will come in the future.

——— ☆ ☆ ☆ ———

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By H. H. KAVELER
Technical Advisor, Phillips Petroleum Company

WHETHER or not an oil producer is familiar with the dictionary definition of the word "efficient," he nevertheless comes to recognize and to depend upon a quality of efficiency in men, machines, and the industrial process that represents the competitive enterprise in which he is engaged. The word is difficult to define, but as it applies to petroleum production, efficiency is a measure of accomplishment of a desired result through the exercise of energy. The desired result is maximum recovery of the petroleum present in any pool consistent with reasonable or decreased cost of production, which means generally, the elimination of waste in petroleum production. The standard of efficiency in any progressive industry is constantly raised to higher and higher levels as technical skill is improved under a system of competitive operation. Although it is usually easy to measure relative efficiency of an operation as between the present and past times, it is difficult to choose and bring into practice new methods that promise improvement in the future. This is particularly true in petroleum production practices.

Oil reservoirs are developed and operated in a much more efficient manner today than they were even a few years ago. New techniques and new facts founded upon the application of scientific principles continue to improve production practices. Perhaps the most important contributions have come in recent years from the study of reservoir behavior and the influence of proper control of reservoirs on the utilization of natural reservoir energy whereby principles of petroleum engineering have been established that have stabilized the economy of the entire industry. One of these principles is that rate of withdrawal from pools is an important factor in fixing the efficiency of the petroleum production operation.

Controlled rate of withdrawal from pools exists as an engineering factor only in periods when potential supply exceeds demand for petroleum. For that reason, adjustment of rate of production as an engineering factor has been possible only since a system of proration was instituted in the several states. Wide open flow of as many wells as operators dared to drill into a pool was, and is, in a period of excess supply, an obviously wasteful practice that results in subsurface and surface loss of otherwise recoverable petroleum. Open flow practices in a period of over-supply also cause a waste of capital resources invested in unnecessary wells and the installation of unnecessary facilities by over-development of pools. Experience under proration has firmly established the fact that control of rate of production is one of the most important factors in accomplishing increased recovery of oil. Beyond that generalization, the technologists of the industry have turned their attention more and more to the problem of determining a specific relationship between rate of withdrawal from a pool and efficiency of the production operation.

Crude oil represented by the petroleum produced into stock tanks or pipe lines has no property that would cause it to flow from reservoir rock into well bores. It must be forced to flow either by some energy source native to the formation or by energy supplied from the surface. Therefore, the first principle in developing efficient production practices recognizes that crude oil, with very few exceptions, is found associated with compressed natural gas existing as free gas or gas in solution in the oil, compressed water, or both, in a common source of supply. Energy stored in compressed gas and/or water is converted into energy of production by allowing the compressed fluids to expand through the oil-bearing section into well bores maintained at a lower pressure. Crude oil is therefore produced because expanding gas or water replaces it in the pore spaces of permeable rock. An oil recovery operation ends when the oil saturation in the initially saturated section is reduced by influx of water or gas to the point beyond which the volume of oil obtained fails to pay well operating costs. The recovery process is, therefore, fundamentally dependent upon two related actions. The first is the conversion of the potential energy stored in compressed fluids into energy of flow by the release of pressure, and, the second is control of the energy dispensing medium so as to maintain the maximum oil saturation between the advancing or expanding energy source and the well bore.

The application of scientific principles to a study of petroleum reservoir performance has brought an increasingly mechanistic attitude toward the fundamental actions that suggests a similarity between a producing reservoir and an engine. A producing reservoir and an engine are alike in the sense that both operate by transforming energy from one form into another, and both accomplish the energy transformation to a degree fixed by certain design and structural features as well as by speed of operation. Though analogies are often misleading, it is convenient to speak in such terms for the purpose of this discussion. Engines are constructed in the pattern of certain basic designs. A somewhat similar situation exists with respect to oil productive reservoirs except that the designs are those created by Nature. With respect to the first fundamental action operators have learned to distinguish between "solution gas drive" type reservoirs in which the principal energy source is compressed gas dissolved in oil, "free gas cap" type in which the principal energy source lies in the gas occupying a large gas-cap over the oil, and "water drive" type reservoirs in which the principal energy source is a large volume of water in permeable contact with the oil-bearing horizon. Each type reservoir should, on theoretical grounds, and actually does in practice, exhibit characteristic behavior reflected by producing gas-oil and water-oil ratios, reservoir pressure decline per unit of fluid produced, and potential decline of producing wells as a function of the recovery obtained. The existence of these three fundamental types predicted by theory has by this time been amply demonstrated by field observation. The paper delivered by Buckley and Craze at the Southwestern District meeting of the A.P.I. presents field data establishing the fact and the necessity for recognizing such types of reservoirs.[1]

In addition to classifying reservoirs as to the type of drive by which energy is to be transformed into energy of flow, it is necessary to distinguish those characteristics of reservoir rock and its petroleum content that influence the efficiency of the energy conversion process involved in the second fundamental action. The solubility-shrinkage characteristics of the petroleum reservoir liquid, the viscosity of the reservoir oil, the oil, gas and water saturation respectively of the permeable reservoir rock, the effective permeability of the rock to oil and gas and water respectively, the permeability profile and the continuity of permeability, the thickness of the oil-bearing section, and dip of the horizon are all design features of the machine created

*Presented before Mid-Continent District American Petroleum Institute, Division of Production, Spring Meeting, Tulsa, Oklahoma, May 20 and 21, 1943.

by Nature that must influence efficiency of operation. As is the case with any actual machine, there is an upper limit of efficiency beyond which an otherwise ideal production operation cannot be carried. One cannot hope, therefore, to recover all crude oil in a reservoir nor can one expect to obtain in actual practice complete conversion of reservoir energy into energy of production. No engine is perfect. Such remarks may appear to be somewhat trivial but they are made for the express purpose of emphasizing that it is almost as easy to adopt an arbitrary view on the standards of efficient operation as it is to disregard utterly the fundamental facts about reservoir behavior and produce petroleum in a wasteful manner. There can be no universal or general standard of efficiency in petroleum production. The industry cannot expect to discover universal permissible gas-oil ratio rules or similar fixed standards of performance as a basis for determining degree of efficiency. For the present, at least, each pool must be considered with respect to the type of energy source available to production and to the characteristics of the reservoir and its contents which determine in a large measure how efficiently that energy may be utilized. What program must be followed in each pool to increase efficiency in operation must then be judged in a competent manner and in the light of reasonable consideration by engineering analysis. Somewhere between wide open flow and no production at all from wells drilled, both situations being wasteful, there must be a rate of withdrawal which is an efficient rate consistent with reasonable demand for petroleum from the pool.

The criteria for judging the rate of withdrawal that would lead to efficiency are simple enough. Withdrawal from a pool should be adjusted to a rate that will conserve reservoir energy. This may be stated in alternate ways. It may be said withdrawal should be adjusted to a rate that will maintain the producing gas-oil and water-oil ratios at a minimum. An equivalent statement would be that rate should be adjusted so as to minimize the reservoir pressure decline per unit of petroleum produced. In applying reservoir pressure decline as a measure of conservation of reservoir energy, it is necessary to recognize the limiting performance of the three possible types of drives.[1]

Maintenance of reservoir pressure is not the sole measure of successful reservoir control. The rate that conserves reservoir energy must be subject to further adjustment to a lower rate so as to maintain insofar as possible the normal gravitational segregation of free gas, oil, and water throughout the reservoir. The second and necessary criterion of efficient rate of production is whether or not the rate maintained is such as to maintain a uniform encroachment into the oil-bearing section of either water or gas, whichever is being relied upon as the energy source. Irregular encroachment of water or gas into a reservoir may isolate productive sections, or productive areas, in a manner to render otherwise recoverable oil nonrecoverable. Premature encroachment of water or gas into a well increases operating costs and the economy of operation and also leads to excessive producing gas-oil and water-oil ratios with consequent excessive loss of reservoir energy.

How critical the rate of production factor may be in conserving reservoir energy through conservation of reservoir pressure and in maintaining uniform encroachment of the energy-bearing fluids available to production is a question left for the most part to further study based upon further field tests considered with respect to all of the factors that contribute to efficiency in performance. The theory of reservoir performance is adequate and points clearly to the fact that rate of withdrawal will have a significant influence on the efficiency of operation of most petroleum reservoirs provided reservoirs are developed in a manner to make rate adjustments an economically possible consideration. The practical man must take theory with the usual grain of salt. His faith in the practical value of the conclusions drawn from the theory of reservoir performance developed over the last ten years should be greatly strengthened, however, from the results obtained in proper reservoir control by those who have employed the newer engineering principles. Operators who have taken the time and who have been willing to make the required dollar investment to obtain complete engineering data during the course of developing pools have discovered values by achieving new efficiencies in crude oil production.

The importance of rate to efficient operation has been shown from the practical operating viewpoint most convincingly in pools that have an exceptionally active and effective water drive type of mechanism. The reasons for this are that an active water drive, if it is present, can be readily determined by the simple use of subsurface pressure gauges to obtain reservoir pressure surveys early in the life of the pool, and the response of a water drive reservoir to adjustment in rate of withdrawal is relatively rapid and quite apparent. Control of reservoir pressure decline through adjustment of rate has been accomplished in a number of major pools, particularly East Texas, Yates Pool, and in the Gulf Coast, and, in some instances, rates have been further adjusted for the purpose of maintaining a uniform encroachment of water.

Examples of where adjustment of rates was responsible for improved performance in gas-drive types of reservoirs are not so numerous. Yet, reservoir performance theory indicates that a gas-drive type reservoir, particularly under a gas-cap drive, under proper control should in most instances respond to adjustment of rate under favorable conditions with equal degree of improvement as do water-drive pools, There are several good reasons why good examples of the improved efficiency of gas-drive pools in response to rate adjustments do not exist. The gas-drive mechanism is not as sensitive to rate adjustment by its very nature, nor is it as efficient as water-drive operation. Results obtained in rate adjustment are therefore not usually immediate in gas-drive pools. Furthermore, the results to be obtained in the adjustment of the rate of withdrawal from gas-drive pools must also depend in a very large measure upon the location of the wells drilled in the field and upon restriction of gas production from individual wells, particularly those wells located in the structurally high position which by virtue of that high position may have excessive producing ratios. It would appear, therefore, that before rate adjustment would be effective in gas-drive type pools, steps would have to be taken at the same time to restrict individual wells that produce excessive volumes of gas.

If the daily withdrawal from a reservoir is to be maintained within limits of efficient production fixed by the character of the reservoir and by the nature of its energy source, one necessity immediately suggests itself. Pools must be developed, investments must be made, and operating practices must be such as to permit first a determination of efficient rate, and secondly, some freedom in choice of rate. In too many instances pools are being developed without regard to engineering consideration of the reservoir. When this is done situations are created whereby investment in wells and other facilities require rates of production, to return reasonable profit on investment, that may be higher than conservative rates of withdrawal. When open flow potential is no longer a measure of the worth of a pool, nor a measure of the amount of oil that may be recovered, and, when unnecessary waste of reservoir energy through excessive producing gas-oil or water-oil ratios is no longer a privilege of lease ownership, it will become increasingly important for operators to determine first the type of drive that apparently exists, and, from that the number and location of

wells to be drilled through a careful determination and study of the characteristic reservoir properties. When that sound engineering procedure is adopted, investment can be adjusted and made dependent upon efficient rate. Otherwise, wells are likely to be drilled in wasteful numbers or be located in a manner as to use reservoir energy inefficiently, and rate of withdrawal as a factor in conservation becomes a precluded consideration. The prudent operator will realize the advantages to be gained from sound engineering analysis and will not rely upon the mere drilling of wells in great numbers in the belief that this alone will assure maximum benefits from any discovery.

The principles of reservoir engineering developed in the last ten years have established one fact perhaps more important than all others. A well can be properly regarded now only as one element in the production machine, and, it can function efficiently only when it is by design drilled, completed, and operated in a manner that uses reservoir energy of production effectively. It is more important, therefore, to drill wells at strategic locations with respect to structure and type of reservoir drive than it is to follow a geographical pattern fixed by ownership on the surface. Wells must be drilled to explore structures, establish the reservoir characteristics necessary for a proper analysis of the future reservoir performance and only in such number as to insure an efficient rate of withdrawal consistent with the demand for crude oil production. Efficient development is the forerunner of efficient rate of withdrawal. It is, in fact, quite common in recent years to come to the conclusion that the interest of everyone in a reservoir can be served best by substituting for wells drilled an investment in one type of secondary recovery or another. The success of the number of gas injection projects instituted early in the life of many petroleum reservoirs as well as other secondary projects should be ample evidence that proper engineering analysis of reservoir conditions generally points to considerations more important than the mere drilling of wells.

The technical literature developed in the last ten years is evidence of the growing appreciation of the importance of adjusting investment and operating practices so that every operator may enjoy the advantages of exploiting pools in a conservative manner rather than by individual wells in a wasteful manner. A no more convenient nor instructive compilation of the principles of the new oil production technology exists than that presented by the report of the Special Study Committee on Well Spacing and Allocation of Production of the American Petroleum Institute.[2] That report, available in booklet form, deserves the serious study of everyone interested in conservation oil production practices.

Controlled rate of withdrawal not only provided the fundamental principle upon which the system of proration was brought into existence, but controlled rate of withdrawal has developed into the principle of efficient rate and has proved to be the means bringing proration to its present state of development as a successful regulatory measure. Efficient rate of production is the fundamental basis on which the system of allocation under proration should be based. The respected conclusions of Joseph E. Pogue[3] are in part as follows:

> "In its more advanced areas of application, proration has established the optimum-rate concept as a working principle * * *. Experience has clearly demonstrated that the best results are obtained if the output of each pool is adjusted to its most efficient rate,

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and engineering technique is rapidly developing whereby this criterion can be broadly and effectively utilized. * * *"

Without any intention of detracting from the main conclusions of that author, the following observation may be made. All conceptions of efficiency arise fundamentally from the scientific procedure of constructing models for the purpose of making repeated experiments to provide information that ultimately converges to a conclusion of fact. By that process models of engines are constructed after a variety of designs which, after trial and error tests, lead finally to conclusions that one model representing one design, if operated at a particular speed, will provide the most efficient operation under particularly specified load conditions. This experimental procedure is the foundation of natural science and has been largely responsible for developing our industrial technology. But oil and gas pools can be produced only once. There is no second time when the entire machine can be reassembled and produced over again. For that reason, the oil producer will be forever denied the privilege of determining by actual experience "the most efficient method" or "the most efficient rate" of producing a reservoir.

That does not mean, however, that basic engineering procedures can never be applied to determine new standards and new ways of achieving efficiency in operation. Many scientific facts can still be established and without resorting to completely indirect methods, these facts in the light of experience can be relied upon to develop a more sound production practice. If time is too long, or, if detail in desirable facts are still lacking, there is still that ability to do what the human race has always done—use common sense and judgment in the light of experience. It may be, for the immediate present, that method of concluding that rate of withdrawal does have significant influence on the efficiency of operation, may have to be relied upon.

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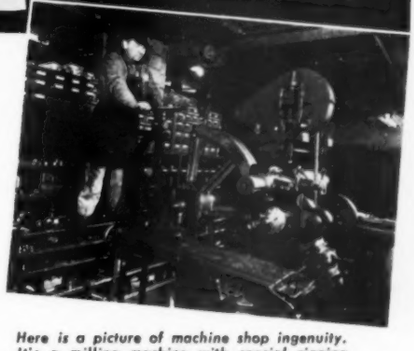

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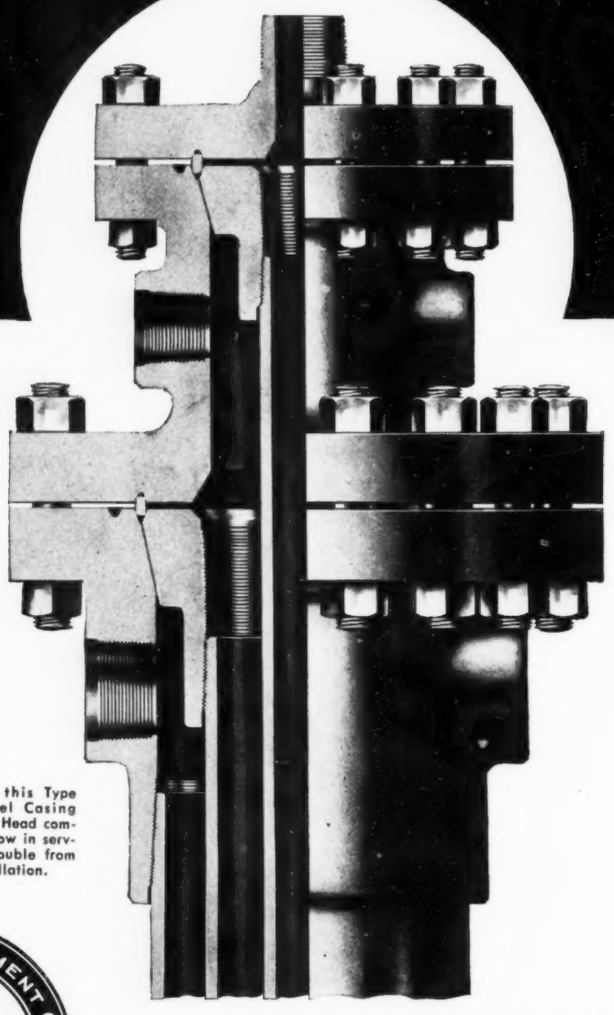

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Determination of Oil-Well Capacities From Liquid-Level Data*

By
CHARLES C. RODD
Gulf Oil Corporation

PRIOR to 1938, proration procedure in Kansas required the physical testing of wells in order to set up a basis for allocating production. Subsequently the use of liquid-level data and bottom-hole pressure data was authorized on certain types of wells as a basis for calculating well capacities, thereby permitting wells to be tested at low rates and with small volumes of production.

This paper gives some attention to the equipment used for obtaining liquid-level data but in general it is devoted to the theoretical and physical factors involved in well testing by drawdown methods. These tests are divided into two classifications: (1) liquid-level data used directly to calculate capacities, and (2) liquid-level data and liquid-level measuring equipment used in connection with other data to determine bottom-hole pressure. Equations and calculations for both types of tests are shown.

Well capacities calculated from fill-up data have not been used generally but offer a simple means of testing some wells. Theoretical factors and calculations for such tests are shown.

In the state of Kansas, proration laws required that the "ability of a well to produce" be given consideration in state allocation orders and for many years this was the only factor used in prorating the allowed oil. The "ability of a well to produce" was the quantity of oil that could be obtained from a well in a prescribed period, usually 24 hr. Early in the history of State-regulated proration, Kansas operators realized that, unless some restriction were placed upon equipment, the competition between producers to obtain large well "potentials" might result in a race to install the largest pumping equipment. Consequently, restrictions were placed upon the size of tubing and length of pump stroke that could be used in pumping wells during potential tests. Later, restrictions were placed also upon the size of tubing and chokes that could be used in flowing wells.

Despite the restriction set-up, better pumping equipment was designed and installed, pumps were improved, and various devices were invoked to obtain high rates of production for short periods of time. By 1937 pumping cycles of forty to forty-five 54-in. strokes per minute were not uncommon, and numerous wells had produced at the rate of 3500 bbl. per day for short periods. Such production was far beyond any rate that could be long sustained. Equipment necessary to take "potentials" was several times larger than that needed for normal producing purposes, and repairs and replacements required by the high pumping speeds were excessive. Also, many operators were beginning to suspect that the high rates of production maintained during "potential" tests were conducive to early water encroachment.

By 1938 large-scale physical testing of wells in Kansas ended, the use of the bottom-hole pressure gauge had become common, engineers and operators were becoming familiar with the term "productivity index," and bottom-hole pressure was being used as a factor in allocation in many areas. There were many drawbacks, however, to large-scale use of bottom-hole pressure gauges for determining well capacities, although numerous operators had used such equipment to obtain engineering data and, from a technical standpoint, had proved that the use of the equipment was feasible.

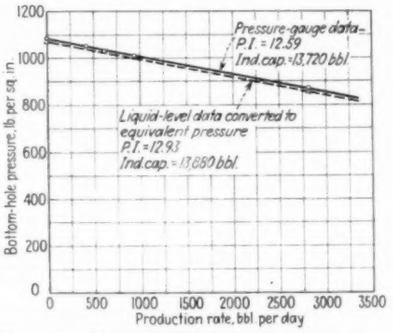


Fig. 1. Comparative pressure-gauge and liquid-level test showing straight-line relationship to 2800 bbl.

Fluid-Level Measuring Equipment

In 1937, representatives of the Depthograph Company conducted experiments in Kansas with equipment that had been used in California to obtain data for determining well capacities. This equipment consisted essentially of: (1) a pressure chamber for releasing a charge of compressed air or gas into the annulus between tubing and casing, thereby setting up a wave front that would be reflected by the liquid surface as well as by fixed objects or reflectors in the well; (2) a diaphragm for detecting wave reflections; (3) apparatus for timing and recording the reflections. At that time measurements were dependent upon velocity calculations and correlation between these and fixed objects in the wells, such as tubing catchers and liner tops. Although the method had been quite successful in California it was not considered suitable for requirements in Kansas, for several reasons, among them the following:

1. Most wells in Kansas did not produce sufficient gas to maintain a homogeneous mass in the annulus above liquid level; velocity computations accordingly were complicated.

2. Few wells were equipped with tubing catchers or objects that could be used for correlation and in most wells liquid levels would have been above such objects had they been used.

3. Velocity computations were not considered accurate enough for official use by proration engineers.

It was known that reflections from tubing couplings could be obtained and as a result of the experiments in Kansas it was decided to make tubing the basis of measurement and modify equipment accordingly.

While the Depthograph Company was developing equipment to determine depths to liquid levels in oil wells, the International Geophysics Company of California developed an instrument—the Echometer—using a cartridge for setting up a wave front, a Tucker hot-wire microphone for detecting wave reflections, and an electrically controlled, direct-recording apparatus for obtaining a record of the wave reflection from tubing collars and liquid levels.

During the early part of 1938 a series of tests was conducted in Kansas with an Echometer. Although the tests brought out some of the deficiencies of equipment and methods, they established the practicability of using tubing collars as a basis of measurements, and the feasibility of testing Kansas Arbuckle dolomite wells by liquid-drawdown methods. In the latter part of 1938, the Kansas Corporation Commission gave official sanction to the use of Depthograph and Echometer equipment for testing certain types of wells. The use of bottom-hole pressure gauges also was approved and, later, a method, known as the "back-pressure method," for determining bottom-hole pressures

*Presented before American Institute of Mining and Metallurgical Engineers, New York, New York, February, 1942.

from liquid levels and other data was included.

A third instrument, called the Sonic meter, for determining depths to liquid level in wells, was developed by the Gulf Oil Corporation. This instrument is electrically controlled; an ordinary blasting cap is used to initiate a wave front, a carbon-button microphone picks up reflections from tubing collars and the liquid level, and an oscillograph transmits the reflections to a camera recording device.

The development of liquid-level measuring equipment provides a ready means of measuring the liquid drawdown of a producing oil well. All of the instruments can, under proper conditions and within varying limits, determine the number of tubing couplings between the wellhead and the liquid level. Knowing the length of the tubing joints, it is then a simple matter to compute the distance to the level of liquid in the annulus. The relationship of these data to bottom-hole pressure and to well testing involves numerous factors.

Factors in Well Testing

"Potentials" determined from bottom-hole pressure or liquid-level measurements are based on a straight-line relationship between pressure at the bottom of the well and the rate of production. Under certain conditions, liquid levels are proportional to pressures and the height of the liquid column may be substituted therefor. Well tests utilizing the relationship between pressure, or liquid level, and production rate eliminate the necessity for high rates of production. Tests taken in this manner have commonly been referred to as drawdown tests; that is, a drawing down of the pressure or liquid level by increasing the rate of production.

When the drawdown of pressure or liquid level is directly proportional to liquid production, the pressure-flow relationship may be expressed by a constant, commonly called the "productivity index," which is usually expressed in barrels per day per pound reduction in bottom-hole pressure, or barrels per day per foot drawdown.

In all but a few of the tests made in several thousand wells in Kansas the relationship between pressure and liquid production approximated a straight line between the limits of the production rates obtained. Numerous wells, with liquid capacities up to 2000 bbl. per day, have been tested to near capacity without deviating from the straight-line relationship, and tests made on wells producing as much as 2800 bbl. per day show no deviation (Fig. 1). Many wells have shown exceptionally large indicated capacities when drawdown data were extrapolated to zero

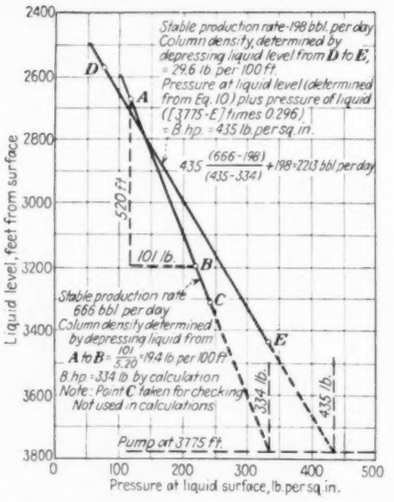

Stable production rate-198 bbl. per day
Column density, determined by depressing liquid level from D to E, = 29.6 lb. per 100 ft.
Pressure at liquid level (determined from Eq. 10) plus pressure of liquid ([3775-E] times 0.296) = B.hp. = 435 lb. per sq. in.
435 (666-198)/(435-334) + 198 = 2213 bbl. per day
320 ft.
101 lb.
Stable production rate 666 bbl. per day
Column density determined by depressing liquid from A to B = 101/5.20 = 19.4 lb. per 100 ft.
B.hp. = 334 lb. by calculation
Note: Point C taken for checking. Not used in calculations.
334 lb.
435 lb.
Pump at 3775 ft.
Liquid level, feet from surface
Pressure at liquid surface, lb. per sq. in.
2400
2600
2800
3000
3200
3400
3600
3800
0
100
200
300
400
500
A
B
C
D
E

Fig. 2. Graphic illustration of back-pressure method of determining bottom-hole pressure

bottom-hole pressure, and the accuracy of such indicated capacities has been questioned. Facilities for obtaining comparative data between drawdown and physical tests at rates above 3000 bbl. per day have not been available and for this reason, and others, it was considered advisable to set a maximum rating of 3000 bbl. for wells tested in Kansas by the drawdown method.

The straight-line relationship between pressure and producing rate may be expressed algebraically as follows:

$$C = \frac{Q}{P_r - P_p} \quad . \quad . \quad . \quad . \quad (1)$$

Where:

C = productivity index factor, bbl. fluid per day per lb. pressure drop,
P_r = static reservoir pressure, lb. per sq. in.
P_p = equilibrium bottom-hole pressure, lb. per sq. in. at stable flow rate Q, and
Q = production rate, bbl. fluid per 24 hr.

Then:

$$Q_{max} = CP_r \quad . \quad . \quad . \quad . \quad . \quad (2)$$

Also:

$$C = \frac{Q_2 - Q_1}{P_1 - P_2} \quad . \quad . \quad . \quad . \quad (3)$$

Where:

Q_1 = oil-production rate, bbl. per 24 hr. at pressure P_1, and
Q_2 = oil-production rate, bbl. per 24 hr. at pressure P_2.

From this equation the well capacity may be expressed as:

$$Q_{max} = CP_1 + Q_1 = CP_2 + Q_2, \text{ etc.} \quad (4)$$

Thus the factors needed for determining a well's capacity are the stable pressures at two producing rates, or the static pressure and stable pressure at one rate. For accuracy in testing, the former is preferred.

The components of bottom-hole pressure are: (1) the pressure due to the weight of the liquid column in the annulus, (2) the pressure due to the weight of gas in the annulus and (3) the pressure at the wellhead. Algebraically:

$$P_{bh} = hd + P_g + P_{ch} \quad . \quad . \quad . \quad (5)$$

Where:

P_{bh} = bottom-hole pressure, lb. per sq. in.,
h = height of liquid column, ft.,
d = mean column weight of liquid, per ft. per sq. in.,
P_g = pressure due to weight of gas column, lb. per sq. in., and
P_{ch} = pressure at wellhead, lb. per sq. in.

Tests From Liquid Levels Only

In certain types of wells, notably Arbuckle dolomite wells in Kansas, operated under controlled condition, the density of the liquid column in the annulus between tubing and casing remains constant at varying rates of production. In such wells the change in pressure due to the weight of the gas column becomes negligible and the wells usually can be produced with zero casinghead pressure. Under such conditions, factors 2 and 3 in equation 5 may be neglected and bottom-hole pressure considered proportional to the height of the liquid column. Then:

$$C_1 = \frac{Q_1}{h_1 - h} \quad . \quad . \quad . \quad . \quad (6)$$

Where:

C_1 = productivity index, bbl. per day per ft. drawdown,
Q_1 = production rate, bbl. liquid per day,
h = distance from wellhead to static liquid level, ft., and
h_1 = distance from wellhead to liquid level at production rate Q_1, ft.

and

$$Q_{max} = C_1(L - h) \quad . \quad . \quad . \quad (7)$$

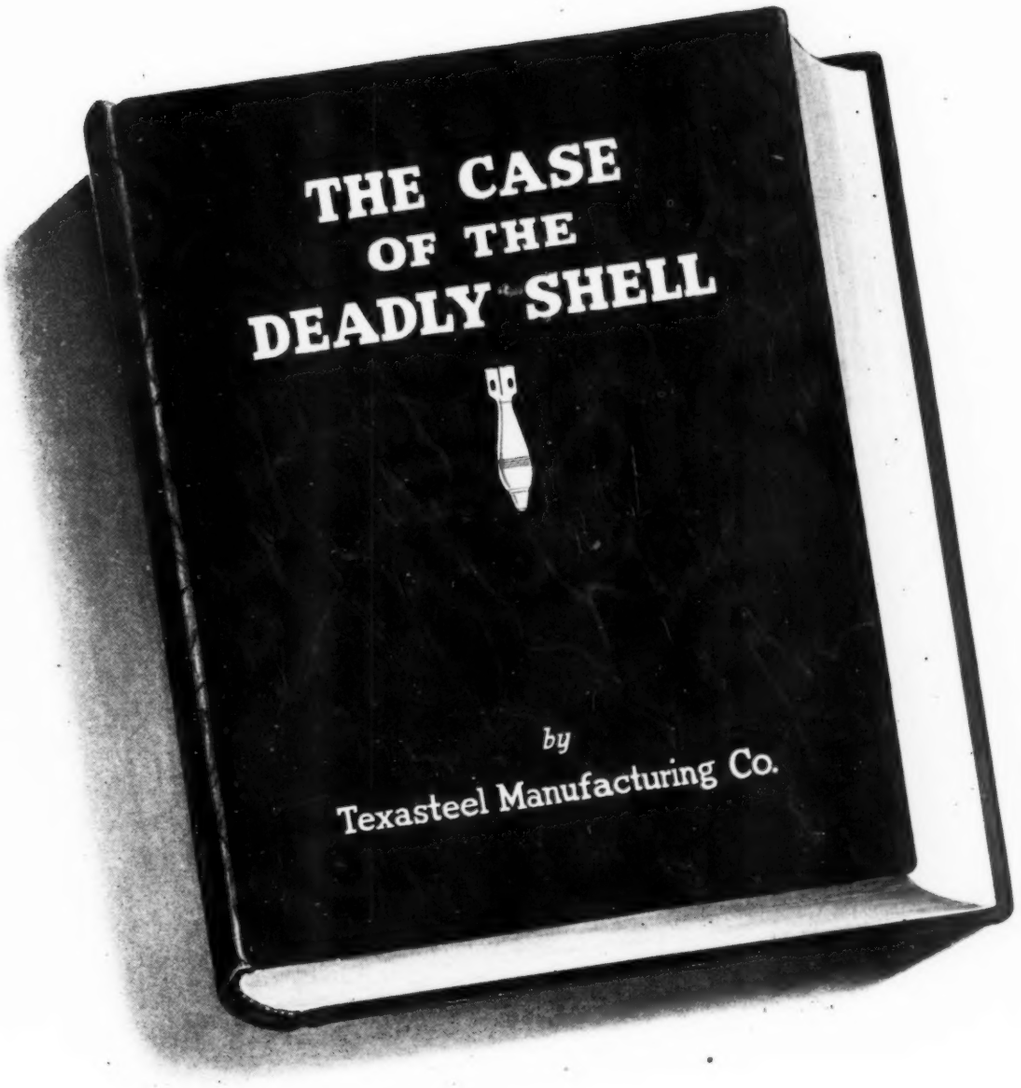
Where:

L = depth from wellhead to top of producing formation, ft.

The use of static liquid levels has not been found satisfactory in most places because many wells produce water and, under static conditions, water constitutes part of the liquid in the annulus preventing the density from remaining constant. Under producing conditions oil will tend to displace the water until a stable condition is reached and only oil remains in the annulus. The well must be tubed to the producing formation, of course, so that water will not accumulate below the tubing. When the static level is not used to determine a well's capacity to produce it becomes necessary to determine the liquid level in the well at two producing rates. Then:

$$C_1 = \frac{Q_2 - Q_1}{h_2 - h_1} \quad . \quad . \quad . \quad . \quad (8)$$

where h_1 and h_2 are, respectively, the



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distances in ft. to the stable fluid levels at rates Q_1 and Q_2.
Then:

$$Q_{max} = C_1(L - h_1) + Q_1 = C_1(L - h_2) + Q_2, \text{ etc.} \quad . \quad . \quad (9)$$

In general, tests determined from liquid levels alone have been satisfactory on wells producing negligible quantities of gas where a liquid of constant density can be maintained in the annulus. Most Kansas Arbuckle wells produce no free gas and saturation pressures usually are less than 100 lb. per sq. in. As drawdown tests usually are taken at restricted rates, pressures seldom are reduced so much that appreciable gas is released into the annulus. In order to minimize difficulties met when making tests, Kansas regulations require that wells be tubed to bottom during official tests. Sample data and calculation for a test utilizing liquid-level data only are shown in Fig. 1.

Back-Pressure Method

Wells producing considerable gas with the oil normally have a varying liquid density at different rates of production and normally are produced with some pressure at the wellhead. The height of the liquid column is seldom proportional to the bottom-hole pressure; consequently it cannot be used directly in computing the productivity index and consideration must be given to all the factors in equation 5, either by measuring the pressure directly with a bottom-hole pressure gauge or by determining the three constituents of bottom-hole pressure separately. These can be determined with reasonable accuracy from liquid-level and surface data by the back-pressure method.

Casing pressures can be obtained directly by use of suitable gauges. The determination of the pressure due to the weight of the gas column involves the measurement of the specific gravity of the gas by laboratory methods or, under certain conditions, empirically. One service company has developed an empirical method of determining specific gravity of the gas from the velocity of the wave used to determine the liquid level. The method has given satisfactory results under some conditions but may cause errors when it is necessary to use a compressor to maintain required pressures at the wellhead.

According to C. P. Walker, in U. S. Patent No. 2161733, knowing the pressure at the wellhead and the specific gravity and temperature of the gas in the annulus, the pressure at the liquid surface may be computed from the following equation:

$$\text{Log}_{10}P_b = \frac{SD}{122.82T} + \text{Log}_{10}P_t \quad (10)$$

Where:

P_b = absolute pressure at bottom of gas column (top of liquid surface), lb. per sq in.,
S = specific gravity of gas,
D = length of gas column, ft.,
T = mean temperature of gas, deg. F. abs., and
P_t = casinghead pressure, lb. per sq. in. abs.

By control of the casing pressure, many wells can be produced without an appreciable quantity of liquid in the annulus. In such wells the effect of the liquid column becomes negligible and bottom-hole pressure may be determined from casing pressure and gas-column pressure. However, where it is impossible or impracticable to lower the liquid level to the pump or tubing perforations, consideration must be given to the height of the liquid in the annulus.

The determination of the pressure due to the weight of the liquid involves the establishment of two or more stable liquid levels, while maintaining a constant rate of production, by changing the casing pressure, either by permitting the well to build up pressure or by using a compressor. In this manner casing pressure is substituted for liquid pressure and, by dividing the change in pressure at the liquid surface by the change in liquid level, the column density may be determined. The average density will normally remain constant, if the production rate is constant. The total pressure of the liquid column may be computed by multiplying the column density by the height of the column above the desired datum, which must be at or above the tubing perforations. Any change in annular area may affect the column density of the liquid and a liner in the well may necessitate a separate determination for this section of the liquid column.

Adding the total liquid-column pressure to the pressure determined by equation 10 gives the bottom-hole pressure at that particular rate of production. When the bottom-hole pressure has been determined for two or more stable rates of production, the well capacity may be computed from equation 3 and equation 4 (Fig. 2).

Bottom-hole pressure tests usually require considerably more time than determinations of liquid levels. When bottom-hole pressure gauges are used it is difficult to determine when stabilization of flow has occurred and tests frequently are extended for some hours to assure reliable data. The use of bottom-hole pressure gauges in pumping wells requires pulling and rerunning rods, and occasionally tubing, before and after the tests, thereby involving considerable expense. Also, even under the

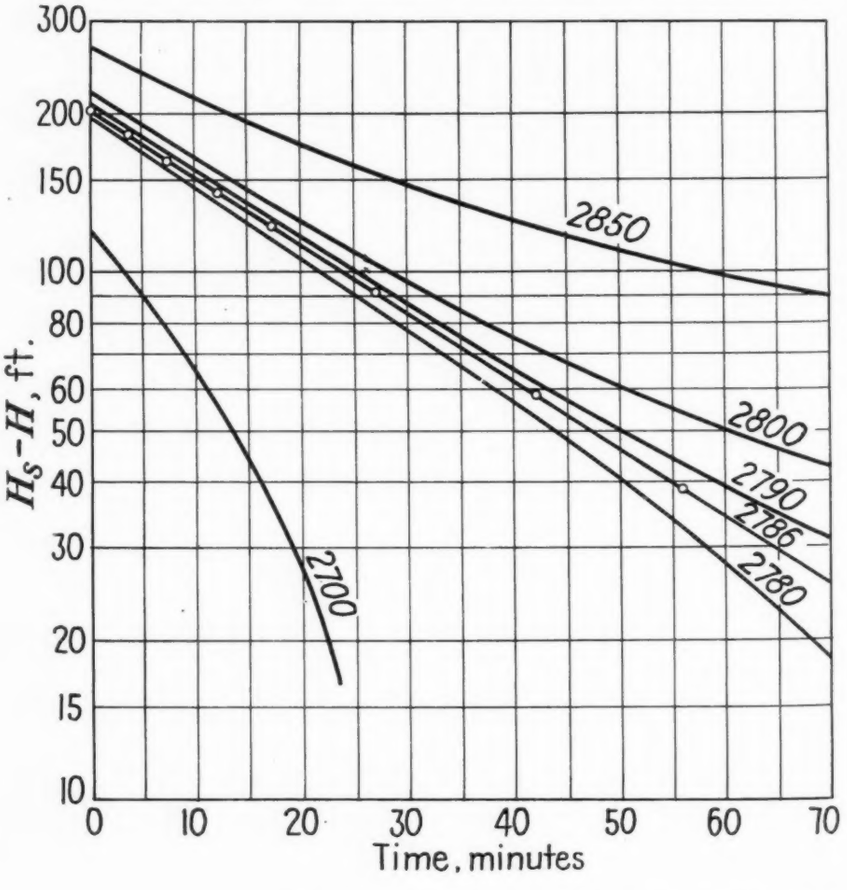

Fig. 3. Determination of static liquid level (H_s) from fill-up data

TABLE I
Sample data and calculations, official Kansas drawdown test
Liquid-level data only

Production data

Period	Hours gauged	Depth to liquid, ft.	Production		24-hr. rate, bbl.
			Liquid, bbl.	Water, percent	
1	3	1,143	92.70	2	742
2	3	952	66.00		528
3	3	850	50.87		407

Well data

Producing formation	Arbuckle dolomite
Well depth, ft	3,284
Depth to top of producing formation, ft	3,272
Casing size, inches o. d	6
Depth to casing seat, ft	3,271
Tubing size, ft	3
Length of tubing, ft	3,281
Number of tubing joints	105
Average length of tubing, ft	30.9
Pump size, in	2¾
Depth of perforations, ft	3,267–3,270

Calculations

Productivity index (low-high rates) $= \frac{742 - 407}{1143 - 850} = 1.143$

P.I. (low-intermediate rates) $= \frac{528 - 407}{952 - 850} = 1.186$

Average P.I. $= \frac{1.143 + 1.186}{2} = 1.165$

Indicated liquid capacity $= (3272 - 850) \times 1.165 + 407$
$= 3229$ bbl. per day

Well rating $= 3000 -$ (2 percent of 3,000)
$= 2940$ bbl. per day

most favorable conditions, the gauges are subject to damage from the shocks and vibration of a pumping well and occasionally tests must be repeated.

Determination of bottom-hole pressure by the back-pressure method sometimes requires a compressor to maintain casing pressure, and when the well itself builds up pressure a regulating valve is necessary to maintain a constant pressure. The liquid-level measuring equipment used for back-pressure tests is essentially the same as for other tests except that it must be designed for high pressures.

Back-pressure and pressure-gauge tests require extreme care, both in obtaining data and in the interpretation and analysis of results. It has been found that, in certain types of wells, conditions arising through acidizing, and the attendant loading of the well, may temporarily affect the normal pressure drawdown, causing the test data to reflect an erroneous index.

Tests From Fill-Up Data

Liquid-level measuring equipment provides a means for obtaining fill-up data on a well. Although the method has not been widely used, and sometimes does not give satisfactory results, many wells that produce little gas and ordinarily can be tested by the liquid-drawdown method can also be tested by use of fill-up data.

The theoretical factors in the procedure for determining capacities from fill-up data were expressed by Muskat[5] in 1936 as follows:

[5]References are at the end of the paper.

$$Q = \frac{AH_s}{T} \log_e \frac{H_s - H_0}{H_s - H} \quad . \quad . \quad (11)$$

Where:

Q = well capacity, cu. ft. per min.,
A = area of pipe or annulus, sq. ft.,
T = time between H_0 and H, min.,
H_s = liquid height above formation at static level, ft.,
H_0 = liquid height above formation at zero time, ft., and
H = liquid height above formation at time T, ft.

From which it follows that:

$$C_x = \frac{A}{T} \log_e \frac{H_s - H_0}{H_s - H} \quad . \quad . \quad (12)$$

Where:

C_x = constant equivalent to productivity expressed in cu. ft. per minute per ft. drawdown.

To convert equation 12 into barrels per day per foot drawdown, the following factors must be introduced:

$$C_1 = \frac{7.48 \times 24 \times 60 \times 2.3}{42 \times 144} \times \frac{A}{T} \times \log_{10} \frac{H_s - H_0}{H_s - H} \quad . \quad . \quad . \quad . \quad (13)$$

$$= \frac{4.1A}{T} \log_{10} \frac{H_s - H_0}{H_s - H} \quad . \quad . \quad (14)$$

Where:

A = area of pipe or annulus, sq. in.

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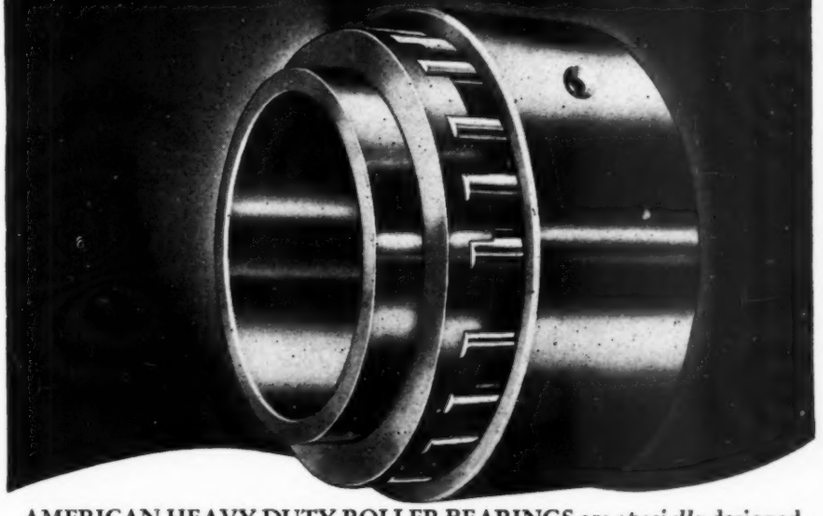

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C_1 = productivity index, bbl. fluid per day per ft. drawdown.

Then:

$$Q_{max} = CH_s \quad . \quad . \quad . \quad . \quad . \quad (15)$$

The determination of H_s—the static liquid level—can be made graphically by plotting $H_s - H$ against T (time in minutes) on semilogarithmic paper with $H_s - H$ on the log scale and time in minutes on the arithmetic scale. Different assumed values of H_s must be used until a straight-line relationship is obtained. The value of H_s that gives a straight line is, theoretically, the true static liquid level. In 60 percent of the tests the straight-line relationship could be obtained and the calculated capacities closely approximated the capacities determined from pumping drawdown tests.

After a straight-line relationship is determined and the true value of H_s is obtained, the productivity index can be calculated by using any two points on the straight-line curve in equation 14. The productivity index can be determined also graphically by the following relationship:

$$C = \frac{I}{K} \times R \times A \times 4.1 \quad . \quad . \quad (16)$$

Where:

K = linear equivalent of one cycle on the log scale, expressed in minutes on the arithmetic scale.

R = slope of line.

Theoretically, liquid-level and time measurements sufficient to establish three points on the graph should be enough to determine the straight-line relationship and well capacity. However, it has been found desirable to obtain a comparatively large number of data to ensure maximum accuracy. Muskat has pointed out also that measurements should not be taken very close to the equilibrium value of H_s because small errors in H will give relatively large errors in the calculated value of C_1 or Q.

Data on a fill-up test and the results of plotting the data on a semilogarithmic chart are shown in Fig. 3 and Table 2.

Drawdown Tests in Kansas

Fluid-level tests. For the initial test of a well, liquid levels at three stable rates of production must be determined. The lowest rate of production must be at least 5 bbl. per hour; the intermediate and high rates must be at least 10 and 15 bbl. per hour, respectively. A spread of 10 bbl. per hour between high and low rates and 4 bbl. per hour between any two rates is required. (Exceptions are made for wells with capacities of less than 30 bbl. per hour.) Stabilization of the liquid level, within a limit of 5 ft. per hour, is required for each production rate and the well must be gauged for 3 hours at each rate after stabilization is reached.

TABLE 2

Data and calculations, fill-up test

Time	Depth to liquid, ft.	Liquid in hole, ft.	$H_s - H$		
			H_s = 2790	H_s = 2780	H_s = 2786
0	722	2,581	209	199	205
3′-25″	702	2,601	189	179	185
6′-55″	681	2,622	168	158	164
11′-55″	659	2,644	146	136	142
16′-55″	640	2,663	127	117	123
26′-55″	609	2,694	96	86	92
41′-55″	576	2,727	63	53	59
56′-55″	556	2,747	43	33	39

Casing (7 in.) 24 lb. bottomed at 3303 ft.
Total depth, 3319 ft.
Tubing (3 in.) 9.30 lb. upset.
Area of annulus, 21.91 sq. in.
Calculations (H_s = 2786):

$$C = \frac{4.1 \times 21.91}{56.9} \text{Log}_{10} \frac{205}{39} = 1.138$$

Capacity = 1.138 × 2786 = 3170 bbl. per day.
(Capacity determined by drawdown test was 3317 bbl. per day.)

The productivity indices between the low and high rate and the low and intermediate rates are determined and the average of the two used to compute the capacity. (A retest may be required if the difference between the indices is more than 10 percent of the higher one.) If the calculated capacity is less than 3000 bbl. of fluid per day the well is given a rating equal to the calculated capacity if no water was produced. If water was produced the rating is reduced by the percentage of water produced during the highest rate of production. If the calculated capacity is more than 3000 bbl. per day the well is given a rating of 3000 bbl. minus the percentage of water.

On subsequent tests only two rates of production are required. The high rate must be at least 15 bbl. per hour and a spread of 10 bbl. per hour between high and low rates is required. Other conditions are the same as for initial tests. All wells must be tubed to the top of the producing formation during official tests.

Bottom-hole pressure tests. Either a bottom-hole pressure gauge or the back-pressure method may be used. Pressures at two stable rates of production are required, and bottom-hole pressures must not vary more than 3 lb. per hour during each gauging period. The high rate must be at least 15 bbl. per hour and a spread of 10 bbl. per hour between high and low rates must be obtained. The high rate must be taken first and the stable period must be preceded by the production of 240 bbl. of liquid. Three-hour gauges at each rate are required. The maximum rating is 3000 bbl. per day with a deduction for water production on the same basis as for fluid-level tests. Wells must be tubed to the top of the producing formation.

Liquid-Level Measurements

The advantages of conducting well tests without interfering with production are apparent, particularly where production is not restricted and down time means loss of income. Even where runs are restricted and down time does not involve loss of allowable, the expense of pulling rods and tubing is more than the cost of an extended study with liquid-level measuring equipment, which in Kansas has been largely used in connection with official tests for allocation purposes. Prior to the use of drawdown tests, physical tests were required, which on most pumping wells necessitated the installation of large-capacity equipment costing from $7000 to $12,000 per well, and required pumping the wells at rates that often were considered to be injurious to the reservoir. As well allowables were extremely low, the capacity of the equipment was not utilized, except for physical tests, for several years after installation. Since the adoption of drawdown tests, most operators are installing smaller equipment costing from $2000 to $5000 per well, and are pumping the wells at much lower rates than formerly.

The service cost of testing a pumping well varies from approximately $40, where liquid-level data alone are used, to approximately $140 for a back-pressure test requiring the use of a compressor. Labor cost varies from $10 to $25, depending on the type of test. The average cost of taking capacity physical tests, including labor and repairs to equipment, but excluding depreciation of pumping equipment, is approximately $125 per well.

Most flowing wells (and some pumping wells if properly equipped) can be tested more cheaply with bottom-hole pressure gauges than with liquid-level measuring equipment. Pressure gauges, however, are costly, and only a few operators own them.

Acknowledgments

The author wishes to acknowledge the cooperation of the Conservation Department of the Kansas Corporation Commission; The Depthograph Company, George Vaughn, Manager, Great Bend, Kansas; and The Halliburton Oil Well Cementing Company.

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The Effect of Casing Perforations on Well Productivity*

By

MORRIS MUSKAT
Gulf Research and Development Company

Abstract

ANALYTICAL calculations have been carried out on the effect of casing perforations on the productivity of wells, and formulas have been derived for general types of perforation patterns. The numerical calculations, however, show that the resultant well productivity is essentially independent of the perforation pattern, but is determined mainly by the total perforation density. Thus, for example, for a density of three perforations per foot of casing, the well productivity will be cut to one-third of that of the uncased well for a perforation radius of ⅛ in., and to approximately one-half for a perforation radius of ¼ in., regardless of the detailed manner in which the perforations are distributed over the casing surface. The analytical theory is also extended to include wells completed with slotted liners. It is shown that the reduction in productivity due to such liners will be relatively small as compared with that due to perforated casings.

Introduction

The increasingly important role being played by productivity factors of wells in determining well potentials and in the general evaluation of producing formations lends interest to the analysis of all the various factors that may influence the productivity of a well. In recent papers[1] the results have been given of theoretical studies made to determine the effect on the productivity factor of a well of the gas-oil ratio of the production and the connate water within the sand. These have served to show that both of these factors may, under suitable conditions, materially reduce the effective productivity factors below those that would be anticipated on the assumption that the wells produce homogeneous fluids.

In this paper will be presented the results of the analysis of an entirely different factor influencing the productivity of a well. This refers to that resulting from the increased use of the method of completing wells by setting casing opposite all of the productive strata and then gun-perforating the particular zones of immediate interest. The practical success of this method of completion would appear to be an answer to the question as to whether it seriously reduces the well productivity or materially cuts down the ultimate oil recovery that may be derived from the producing section. Nevertheless, it is of interest to examine just how great the effect of the restricted flow channels, represented by the gun perforations, may be in increasing the overall effective sand resistance. Of course, to the extent that the well potentials are severely restricted by proration regulations, minor reductions in well productivities are even less serious than if the wells were to be allowed to produce wide open. On the other hand, even under these circumstances there may be at least the academic interest in such calculations in being able to correct and evaluate the effect of the perforations in order to carry out quantitative comparisons between the observed productivity factors and those that might be predicted on the basis of core analyses.

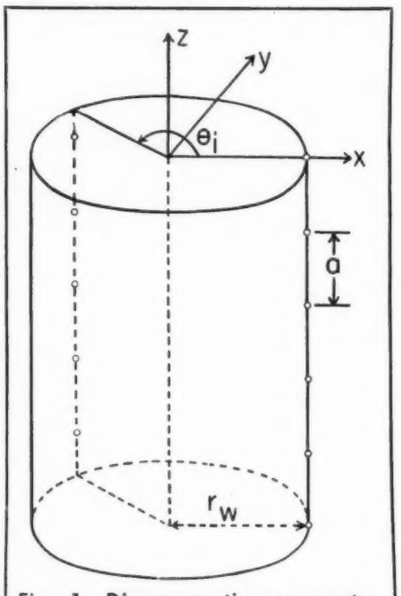


Fig. 1. Diagrammatic representation of a spiral perforation pattern

Analytical Theory

In the following analysis, the three-dimensional character of the flow into a well whose only ultimate outlets to the well bore are the casing perforations will be fully taken into account. Nevertheless, it will considerably simply the computations to suppose that the perforations uniformly extend over the whole thickness of the producing section, and that, in fact, the bounding planes of the producing section form planes of symmetry with respect to the perforations. On the basis of this assumption, we may take the producing zone to be of indefinite thickness, and consider the perforations to lie along indefinitely extended lines covering the whole section, and then ultimately express the results in terms of unit sand thickness. Moreover, to investigate general types of perforation patterns, even though they are not commonly employed in practice, we shall present the general theory for a staggered or spiral system of perforations with an arbitrary number of perforations per pitch of the spiral. Such a pattern may be diagrammatically represented as in Fig. 1, where θ_i represents the angle to the ith line of perforations, as measured from the base line passing through the x axis. The basic spiral or casing radius will be denoted by r_w, which will also equal the well radius. The common radius of the perforations will be denoted by r_p. The x,y coordinates of the perforations on the ith line will be indicated by (x_i,y_i). The spacing between the perforations along each line will be denoted by a.

The analysis will be carried through for homogeneous fluid systems. The heterogeneous character of the flow in wells producing both gas and oil will decrease somewhat the effect of the perforations in reducing the well productivity. However, the labor of solving the flow problem for the multiphase systems would be so great as to be unwarranted merely on the basis of the increased accuracy of the numerical results.

To obtain the productivity of a producing section with a system of perforations like that described, we shall first determine, at least formally, the pressure distribution throughout the system. This will be constructed of a series of basic terms, each representing the contribution of a single perforation line. The latter will be represented analytically as an infinite linear vertical column of sinks situated at (x_i,y_i) with a sink (or perforation) spacing of a. Each such pressure-distribution term, as well as the composite sum, will be a solution of La Place's equation. This representation does not explicitly take into account the fact that the sinks are embedded in an impervious surface, the casing. However, as will be shown in the Appendix, the mutual interference between the various sinks representing

*Presented before American Institute of Mining and Metallurgical Engineers, Austin, Texas, October, 1942.

[1] "Calculation of Productivity Factors for Oil-Gas-Water Systems in the Steady State," H. H. Evinger and M. Muskat. *Trans.* A.I.M.E. (1942) 146, 126-138, 194-203.

the perforations effectively prevents flow between the sinks as if the region between them were actually impermeable.

The pressure distribution for a system of m perforations per pitch may, therefore, be formally expressed as:

$$p = \sum_{o}^{m-1} p_i \qquad (1)$$

where:

$$p_i = \frac{-4q}{a}\left[2\sum_{n} K_o(2n\pi\rho_i)\cos 2n\pi\left(w - \frac{i}{m}\right) + \log 2/\rho_i\right] \qquad (2)$$

where:

$$\left.\begin{aligned} \rho_i^2 &= \frac{(x-x_i)^2 + (y-y_i)^2}{a^2}; \\ y_i/x_i &= \tan\theta_i;\ x_i^2 + y_i^2 = r_w^2; \end{aligned}\right\} \begin{aligned} w &= z/a \\ \rho_w &= r_w/a \end{aligned} \qquad (3)$$

and K_0 is the zero order Hankel function. This expression is that previously developed in the general analysis of three-dimensional homogeneous flow systems.[2] The factor q represents the flux strength of each sink corresponding to a perforation, and ultimately will be eliminated from the calculation of the well productivity.

The value of the pressure given by equations 1 and 2 at points distant from the well, and in particular at a large radius r_e, representing the reservoir radius, is

$$p_e = -\frac{4mq}{a}\log\frac{2}{\rho_e} \qquad (4)$$

where ρ_e has been substituted for $\frac{r_e}{a}$.

Equation 4 represents an approximation in which the series term, which decreases exponentially with the radial distance, has been dropped as compared with the logarithmic term. To this approximation the contribution to the effective reservoir pressure will be the same for each perforation line, and also will be essentially independent of the vertical coordinate.

Since by symmetry all the individual perforations are identical, the well pressure may be determined by focusing the attention upon just one of the perforations; namely, that along the zero line lying on the x axis. For the pressure contribution at this performation, due to its own line, we must take $\rho_o = \rho_p = \frac{r_p}{a}$. For the contributions due to the other perforation lines, the appropriate value of ρ_i may be readily shown to be given by:

$$\rho_i = 2\rho_w \sin\frac{\theta_i}{2} \qquad)$$

The resultant well pressure due to the whole perforation system will, therefore, become:

$$p_w = \frac{-4q}{a}\left[2\sum K_o(2n\pi\rho_p) + 2\sum_{1}^{m-1}(i)\sum_{1}(n)K_o\left(4n\pi\rho_w\sin\frac{\theta_i}{2}\right)\cos\frac{2n\pi i}{m} + \log 2/\rho_p - (m-1)\log\rho_w - \sum_{1}^{m-1}\log\sin\frac{\theta_i}{2}\right] \qquad (6)$$

The resultant pressure differential, therefore, will be:

$$p_e - p_w = \Delta_p = \frac{4q}{a}\left[2\sum K_o(2n\pi\rho_p) + 2\sum_{1}^{m-1}(i)\sum_{1}(n)K_o\left(4n\pi\rho_w\sin\frac{\theta_i}{2}\right)\cos\frac{2n\pi i}{m} + \log\frac{\rho_e}{\rho_p} + (m-1)\log\frac{\rho_e}{2\rho_w} - \sum_{1}^{m-1}\log\sin\frac{\theta_i}{2}\right] \qquad (7)$$

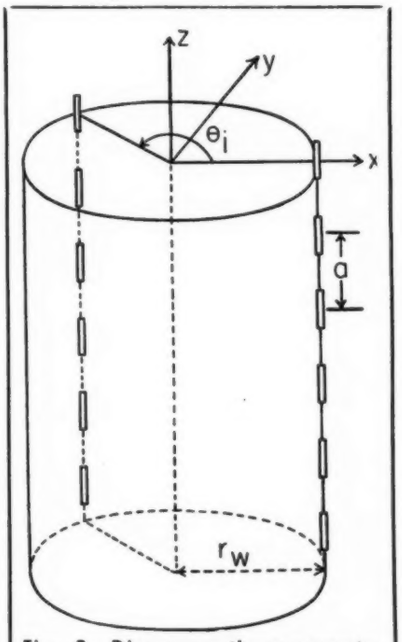


Fig. 2. Diagrammatic representation of a coplaner slotted-liner system

Now the total flux through the system per unit sand thickness will be given by:

$$Q = 2\pi\frac{k}{\mu}\left(\frac{r\partial p}{\partial r}\right)r_e = \frac{8\pi mqk}{a\mu} \qquad (8)$$

Eliminating q between equations 7 and 8, we find:

$$Q = \frac{2\pi mk\Delta p}{\mu}\left[2\sum K_o(2n\pi\rho_p) + 2\sum_{i}\sum_{n} K_o\left(4n\pi\rho_w\sin\frac{\theta_i}{2}\right)\cos\frac{2n\pi i}{m} + \log\frac{\rho_e}{\rho_p} + (m-1)\log\frac{\rho_e}{2\rho_w} - \sum\log\sin\frac{\theta_i}{2}\right]^{-1} \qquad (9)$$

Introducing now the notation defined by:

$$mC = 2\sum K_o(2n\pi\rho_p) + 2\sum\sum K_o\left(4n\pi\rho_w\sin\frac{\theta_i}{2}\right)\cos\frac{2n\pi i}{m} + \log\frac{\rho_w}{\rho_p} - \sum\log 2\sin\frac{\theta_i}{2} \qquad (10)$$

Q can be expressed by:

$$Q = \frac{2\pi k\Delta p/\mu}{C + \log\frac{\rho_e}{\rho_w}} \qquad (11)$$

Recalling now the well-known radial flow formula giving the flux or production rate from an uncased well:

$$Q_o = \frac{2\pi k\Delta p/\mu}{\log\frac{\rho_e}{\rho_w}} \qquad (12)$$

we finally obtain for the ratio of the productivity of the cased and perforated well to that of the uncased well

$$\frac{Q}{Q_o} = \frac{\log\rho_e/\rho_w}{C + \log\rho_e/\rho_w} \qquad (13)$$

This is our final equation giving the relative theoretical productivity factor for the cased and perforated well. The reduction in productivity due to the casing and perforations is represented by the constant C, for if the latter be 0, $\frac{Q}{Q_o}$ equals unity and the effect of the perforations vanishes. The numerical problem of evaluating the effect of the perforations thus reduces to that of determining the magnitude of C as a function of the perforation system.

A check upon the form of equation 11, and in particular the value of C given by equation 10, is provided by the limiting case when a approaches 0. In this case the perforations along each of the several lines merge and the system becomes two-dimensional, corresponding to a battery of wells of radius r_p, distributed uniformly along the circumference of a circle of radius r_w. Since the Hankel function series of equation 10 vanishes as a approaches 0, the value for C reduces to the form given by

$$mC = \log\frac{r_w}{r_p} - \sum\log 2\sin\frac{\theta_i}{2} \qquad (14)$$

As it should, this expression agrees with that previously derived for the corresponding problem of a battery of wells in a two-dimensional system (ref. 2).

For numerical purposes it is convenient to write out the values for C for the different systems corresponding to different numbers of perforations per pitch or spiral unit, as follows:

$\underline{m = 2}$

$$\theta_1 = \pi;$$

[2] "Flow of Homogeneous Fluids Through Porous Media," Cf. M. Muskat. McGraw-Hill Book Company, New York, 1937.

Perforation lines separated by 180°

$$C = \sum K_o(2n\pi\rho_p) + \sum K_o(4n\pi\rho_w) \cos n\pi + \tfrac{1}{2} \log \frac{\rho_w}{2\rho_p} \quad (15)$$

$m = 4$

$$\theta_1 = \frac{\pi}{2};\ \theta_2 = \pi;\ \theta_3 = \frac{3\pi}{2};$$

Perforation lines spaced at 90° intervals.

$$\left.\begin{aligned} C = {} & \tfrac{1}{2} \sum K_o(2n\pi\rho_p) \\ & + \sum K_o(2\sqrt{2}\, n\pi\rho_w) \cos \frac{n\pi}{2} \\ & + \tfrac{1}{2} \sum K_o(4n\pi\rho_w) \cos n\pi \\ & + \tfrac{1}{4} \log \frac{\rho_w}{4\rho_p} \end{aligned}\right\} \quad (16)$$

$m = 8$

$$\theta_1 = \frac{\pi}{4};\ \theta_2 = \frac{\pi}{2};\ \theta_3 = \frac{3\pi}{4};\ \theta_4 = \pi;\ \theta_5 = \frac{5\pi}{4};\ \theta_6 = \frac{3\pi}{2};\ \theta_7 = \frac{7\pi}{4};$$

Perforation lines spaced at 45° intervals.

$$\left.\begin{aligned} C = {} & \tfrac{1}{4} \sum K_o(2n\pi\rho_p) \\ & + \tfrac{1}{2} \sum K_o(1.5308n\pi\rho_w) \cos \frac{n\pi}{4} \\ & + \tfrac{1}{2} \sum K_o(2\sqrt{2}\, n\pi\rho_w) \cos \frac{n\pi}{2} \\ & + \tfrac{1}{2} \sum K_o(3.6956n\pi\rho_w) \cos 3\frac{n\pi}{4} \\ & + \tfrac{1}{4} \sum K_o(4n\pi\rho_w) \cos n\pi \\ & + \tfrac{1}{8} \log \frac{\rho_w}{\rho_p} - 0.2600 \end{aligned}\right\} \quad (17)$$

Because of the small values of ρ_p that will be of practical interest, it is not convenient to sum directly the series of Hankel functions with argument ρ_p. An analytical summation has therefore been used with the following results:

$1/\rho_p$	6	12	24	48	96	192	384
$\Sigma K_o(2n\pi\rho_p)$	0.5383	1.6980	4.3528	10.0065	21.6604	45.3134	92.9671

The series of Hankel functions with arguments involving ρ_w were summed directly, as they converge very rapidly.

The calculations were carried out for well or casing radii of 3 and 6 in.; for perforation radii of ⅛ and ¼ in.; and for perforation spacings a of 1½ in., 3 in., 6 in., 12 in., and a limiting value of 0. The results are plotted in Figs. 3 and 4.

Coplaner Perfection Patterns

If there is no mutual staggering of the perforations in the various lines—i.e., if the perforations in the several lines all lie in parallel planes normal to the axis of the well bore—the analysis can be carried through in exactly the same manner as for the spiral perforation pattern just discussed. The only change introduced by this simplification is that from equation 6 down the cosine coefficients in the multiple Hankel function series should be replaced by unity. When this change is made and the computations repeated, it is found that for the perforation spacings a of the range of practical interest there is no significant difference whatever from the results previously derived for the spiral perforation patterns. The numerical differences become noticeable only for values of a appreciably exceeding 12 in. if the other parameters of the system be kept the same as those used in the consideration of the spiral perforation pattern. It may, therefore, be concluded that the effectiveness of the perforation pattern is independent of the spiral character of the pattern.

Slotted Liners*

Thus far we have considered bullet-type perforations, which could be represented mathematically by series of point sinks. By a slight extension of the analysis, however, the treatment can be generalized so as to include slotted liner systems. For simplicity we shall outline here the analysis pertaining only to coplaner slot patterns, such as are diagrammatically shown in Fig. 2. The only basic change that needs to be made in the previous analysis is that instead of the pressure-distribution term describing a perforation line as given by equation 2, one must use for a linear system of slots a basic pressure-distribution term given by:

$$p_i = \frac{-4q}{a}\left[2\sum K_o(2n\pi\rho_i)\int_{-h}^{+h} \cos 2n\pi(w-\alpha)d\alpha + 2h \log 2/\rho_i\right] \quad (18)$$

where the common slot length $2h$ is ex-

*Model studies of slotted-liner producing systems have been described by F. G. Miller [*Trans.* A.I.M.E. (1941) 142, 137-151]. Unfortunately, however, the results of these investigations are not presented in a form that permits a comparison with those given here.

Fig. 3. Effect of casing perforations on well productivity Q/Q₀=(productive capacity of cased and perforated well)/(production capacity of uncased well). m=number of perforation lines around casing circumference. For solid curves, casing radius=3 in.; for dashed curves, casing radius=6 in.; perforation radius=¼ in. in all cases.

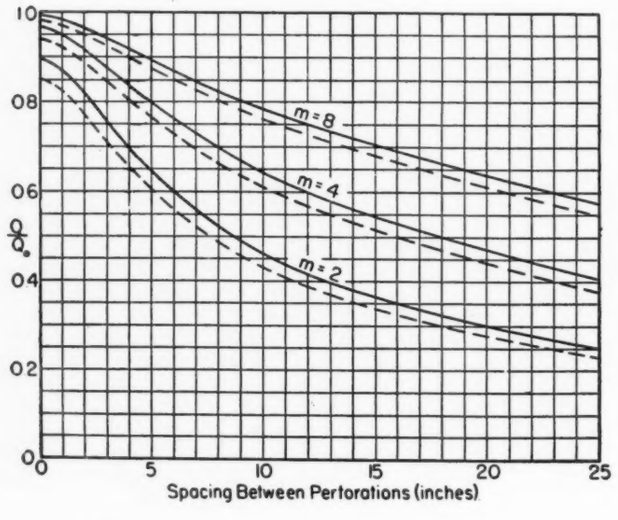
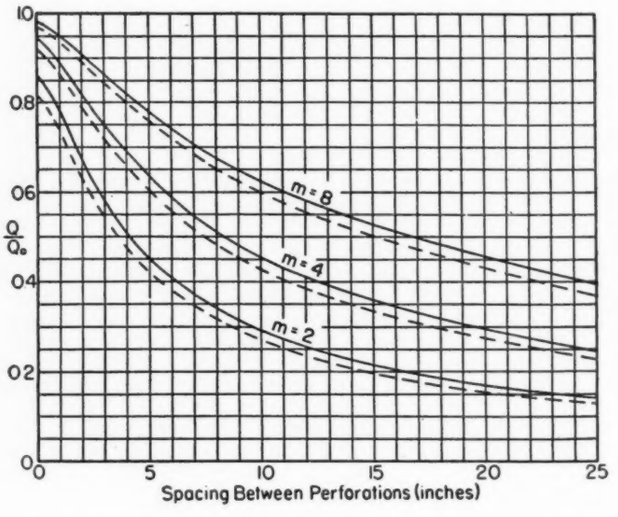


Fig. 4. Effect of casing perforations on well productivity Q/Q₀=(productive capacity of cased and perforated well)/(production capacity of uncased well). m=number of perforation lines around casing circumference. For solid curves, casing radius=3 in.; for dashed curves, casing radius=6 in.; perforation radius=⅛ in. in all cases.



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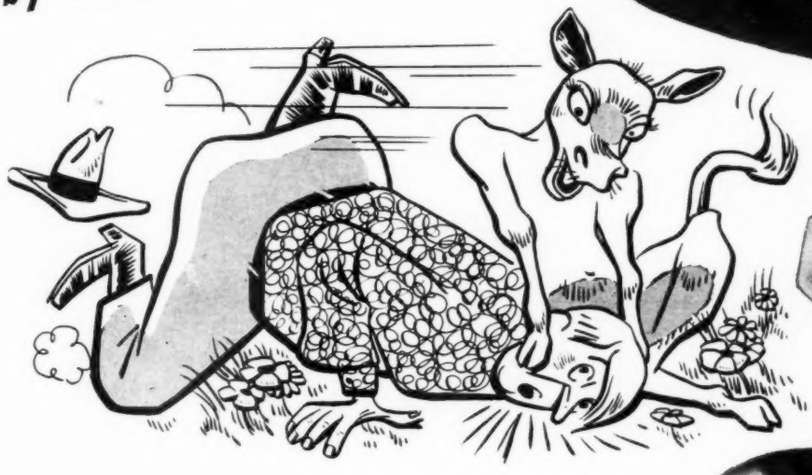

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pressed as a fraction of the mean slot spacing a. Carrying through the rest of the analysis exactly as before, one finally obtains, for the relative productive capacity of the slotted liner system, as compared with that for the uncased sand section, the value given by:

$$\frac{Q}{Q_o} = \frac{\log \rho_e/\rho_w}{C + \log \rho_e/\rho_w} \qquad (19)$$

Here C is defined by:

$$mC = 2\sum K_o(2n\pi\rho_p)\frac{\sin 2n\pi h^*}{2n\pi h} + 2\sum_i\sum_n K_o\left(4n\pi\rho_w \sin\frac{\theta_i}{2}\right)\frac{\sin 2n\pi h}{2n\pi h} + \log\frac{\rho_w}{\rho_p} - \sum \log 2\sin\frac{\theta_i}{2} \qquad (20)$$

where the general notation is the same as previously used, and the symbol ρ_p represents now the half width of the slot expressed in units of the mean slot spacing.

Comparison of this value for C with that for the corresponding perforation system as given by equation 10, with the cosine terms replaced by unity, shows that the change from perforations to slots is represented by the addition of the factors $\frac{\sin 2n\pi h}{2n\pi h}$ before all the Hankel function terms. As these factors are all less than unity, it is clear that the resultant values of C will be smaller here than in the perforation systems, and hence, as is to be expected, the reduction in productivity factor will be less for the slotted than for the perforated casing. To give an idea of the quantitative magnitude of the difference between a slot and perforation pattern, a specific example was chosen in which the mean slot spacing was 6 in., the slot length 4 in. and slot width ¼ in. It was then found that the relative productive capacity for the slotted liner system, with four columns of slots, would be 88 percent whereas that for the corresponding perforated casing would be 59 percent. It thus appears that for all practical purposes a slotted liner may be considered as causing only a negligible reduction in the flow capacity of a producing formation.

Results

As already indicated, the basic results of the calculations are shown in Figs. 3 and 4. The ordinates of these figures are the ratios of the productive capacity, or productivity factor, for the cased and perforated wells to those of the equivalent uncased wells. The abscissas are vertical distances, in inches, between the casing perforations along the various lines of perforations. In carrying through the calculations it was assumed that the effective reservoir radius is 660 ft. The curves of Fig. 3 refer to systems in which the perforation radii are ¼ in. The solid curves are those for an effective casing or well radius of 3 in. whereas that for the dashed curve is 6 in. The three pairs of curves are for patterns involving two, four, and eight vertical perforation lines along the casing circumference. It has been further assumed that the various perforation lines are mutually shifted vertically so as to form a composite spiral perforation pattern. (Cf. Fig. 1.)

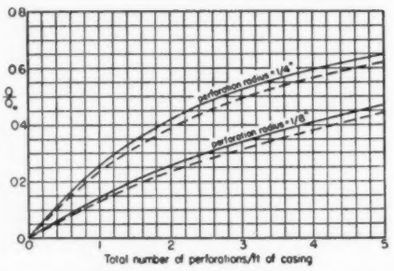

Fig. 5. Effect of casing perforations on well productivity as a function of the over-all density of perforations Q/Q_o = (productive capacity of cased and perforated well)/(production capacity of uncased well). For solid curves, casing radius = 3 in.; for dashed curves, casing radius = 6 in.

The curves of Fig. 4 were obtained for exactly the same conditions as those for Fig. 3 except that the perforation radius was taken as ⅛ in. rather than ¼ in.

Figs. 3 and 4 show that the effect of the perforations may become significant for perforation spacings of the magnitude commonly used in practice. Thus, even for an eight-line pattern of ¼-in. perforations in a 3-in. radius hole, the productivity of the well would be cut to 70 percent of that for the open hole if the spacing along the lines were as great as 16 in.

As is to be expected, the effect of the perforations in reducing the productivity of the well decreases as the number of lines around the circumference increases, provided the spacing in each line remains fixed. It also decreases as the perforation radius increases. Finally, it is to be noted from Figs. 3 and 4 that the perforation pattern represents a relatively greater part of the resistance to fluid flow in the composite sand and casing system for the wells with larger casing than for those with smaller casing, and hence is of less importance in the latter.

As indicated above, a coplaner or non-spiral perforation pattern has, for all practical purposes, exactly the same effect on the well productivity as the spiral perforation pattern. Moreover, as may be checked by direct references to Figs. 3 and 4, it is essentially the total number of perforations over a given sand thickness that determines the reduction in well productivity. Thus, for example, referring to Fig. 3, a cased 25-ft. section of sand, gun-perforated with 100 bullets distributed along two lines 180° apart, and with a perforation spacing of 6 in., will have a productive capacity 60 percent that of the uncased section. If the 100 perforations are distributed with a spacing of 12 in. along four lines spaced at 90° intervals around the circumference, it will still have a relative productive capacity of 60 percent. Finally, if the same 100 perforations were distributed along eight lines, separated by 45° intervals around the circumference, with a spacing within the lines of 24 in., the relative productive capacity would be 59 percent. If only 50 shots were distributed over the 25-ft. interval, the relative productive capacity would be approximately 41.5 per cent for the three different distributions considered here. For smaller perforation spacings, or greater total number of perforations per unit length of casing, there is some spread in the values of Q/Q_o, depending on the number of perforation lines. However, in the range of practical interest, it is the total number of perforations per unit length of sand section, or of casing, rather than the details of the distribution, that determines the well productivity.

The variation of the relative productive capacity with the over-all perforation density is shown in Fig. 5. The curves of that figure represent essentially a replotting of those of Figs. 3 and 4 together with an averaging over the small variations corresponding to the different perforation distributions. There is a tapering off of the rate of rise of relative productive capacity with perforation density as the latter increases; thus, for a perforation radius of ¼ in. and an effective casing radius of 3 in., the relative productive capacity increases only from 41.9 to 59.4 percent on doubling the perforation density from 2 to 4 perforations per foot. However, up to perforation densities of one per foot, the relative productive capacity is approximately proportional to the density.

As was also shown previously, the generalization of the problem of a perforated casing to that of a slotted liner indicates that for all practical purposes the latter may be considered as causing but a negligible reduction in the productive capacity of a well. Thus, whereas a 6-in. casing with perforations ¼ in. in diameter spaced at 6 in. along

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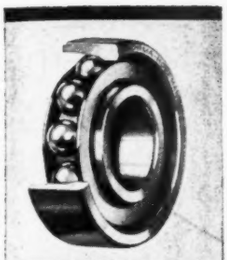
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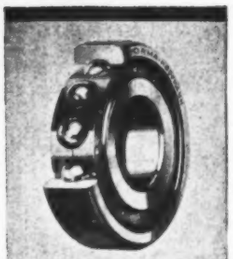
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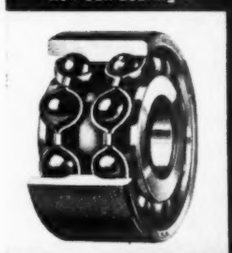

Double Row Ball Bearing

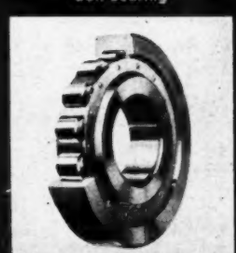
Extra Light Type Ball Bearing

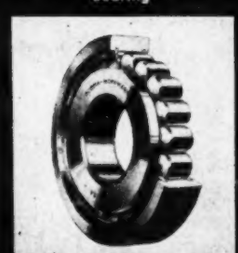
Angular Contact Ball Bearing

Extra Light Single Direction Ball Thrust Bearing

Single Direction Ball Thrust Bearing

Standard Cylindrical Roller Bearing


Type "E" Cylindrical Roller Bearing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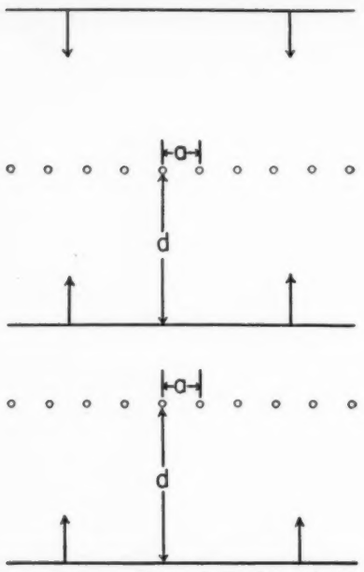
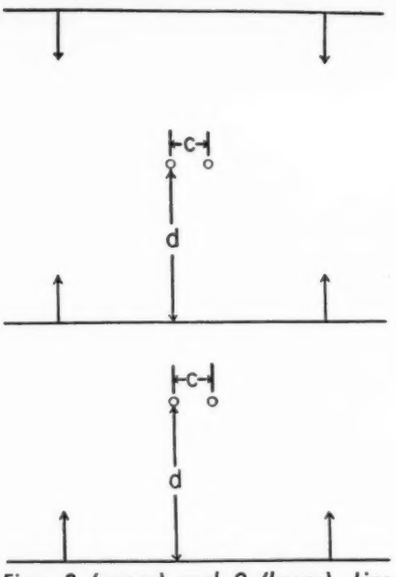


Figs. 6 (upper) and 7 (lower). Line drive into infinite line of wells. No flow across line.

Fig. 6. Symmetrical case

Fig. 7. Unsymmetrical case



Figs. 8 (upper) and 9 (lower). Line drive into pair of wells. No flow across wells

Fig. 8. Symmetrical case

Fig. 9. Unsymmetrical case

four lines would cut the productive capacity of a well down to 59 percent of that of a well with an open hole, the relative capacity will be 88 percent with a 6-in. liner that has four columns of slots ¼-in. wide, 4-in. long and 6-in. mean vertical spacing.

While it is felt that the calculations reported here do indicate correctly the magnitude of the effect of casing perforations on well productivity, it is not to be assumed that the predicted effects will necessarily be observed in field practice. For the actual productivity of a well is the resultant of a great many factors, only one of which is the type of casing perforations, if any. Variations in these other factors—sand permeability, fluid-saturation distribution, gas-oil ratio, cleanliness of sand face, etc.—may well counterbalance and mask completely the limited effect of the casing perforations in making comparisons between cased and open-hole completions even in the same field. The present calculations are based on idealized assumptions and possess no greater validity than these assumptions.

Appendix

In addition to the basic assumption made throughout the analysis presented here, that the production section is carrying a homogeneous fluid, there is another of a purely analytical character. This refers to the fact that the mathematical representation of the perforations as point sinks does not of itself provide for the fact that these sinks are located on an impervious surface; namely, the casing. To have included that fact directly into the analysis would have led to almost insurmountable difficulties. On the other hand, it might appear that unless this were actually done the approximation might be so poor as to be of no value. It is, therefore, of interest to note that for systems with dimensions of practical interest no significant error is introduced by not taking into account explicitly the presence of the casing as an impermeable surface in which are embedded the sinks representing the perforations.

The essence of the argument justifying the use of the method of analysis given here lies in the observation that because of the mutual interference between the multiplicity of perforations comprising the composite network, the latter shields the interior of the casing surface almost completely from inward flow, as if the region between the perforations were actually strictly impermeable. This fact is a consequence of the extremely close spacing of the perforations as compared with the only other physical dimension of interest; namely, the distance of the fluid driving source, i.e., the reservoir radius. It may be demonstrated easily by reference to the equivalent two-dimensional systems. Thus with respect to the vertical shielding—i.e., the prevention of flow between the perforations on the single line—it is appropriate to consider the analogous two-dimensional case of the line drive into an infinite line of wells. In the symmetrical case (Fig. 6), where there is obviously no flow whatever across the line of wells, and where $d/a > 1$, it is easy to show that the flux per well from either side is given by

$$Q = \frac{\pi k \Delta p/\mu}{\log \frac{e^{\pi d/a}}{2\pi r_p/a}} \qquad (21)$$

On the other hand, for the unsymmetrical case shown in Fig. 7, which corresponds to the mathematical representation of our casing perforation problem, it may be shown that the flux per well is

$$Q = \frac{2\pi k \Delta p/\mu}{\log \frac{e^{2\pi d/a}}{2\pi r_p/a}} \qquad (22)$$

As d here corresponds to the reservoir radius r_e in the previous problem, and a to the perforation spacing, it is clear that $d/a >> 1$. A comparison of equations 21 and 22 for this condition immediately shows that the two values of Q are then equal for all practical purposes. This, of course, means that the shielding in the unsymmetrical case of Fig. 7 is complete, and that there is no net flow of appreciable magnitude crossing the line of wells. By analogy, therefore, it may be concluded that for the mathematical representation used above there will be no net flow between the perforations along the lines even though this requirement was not introduced explicitly.

Similar considerations can be applied to the problem of fluid shielding between the several lines. Here the two-dimensional analogy to the extreme case of two perforation lines is a line drive into a pair of wells. For the symmetrical case in which the flow across the line connecting the wells is strictly eliminated (Cf. Fig. 8), the flux per well may be shown to be:

$$Q = \frac{\pi k \Delta p/\mu}{\log d/\sqrt{c r_p}} \qquad (23)$$

where d corresponds to the external radius r_e, c corresponds to the casing diameter, and r_p represents the equivalent of the perforation radius. On the other hand, for the unsymmetrical case (Fig. 9), the flux per well may be shown to be, for $d/c >> 1$:

$$Q = \frac{\pi k \Delta p/\mu}{\log 2d/\sqrt{c r_p}} \qquad (24)$$

It will be clear that here, too, the values of Q as given by equations 23 and 24 are equal for all practical purposes, thus showing that the prevention of flow across the cylindrical surface between the perforations is again automatically taken care of without introducing it directly into the analysis.

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P 521.1
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Corrosion in Distillate Wells*

By T. S. BACON and E. A. BROWN
Lone Star Producing Company

THE typical distillate field requires large amounts of steel pipe, valves, and fittings for its development and operation. Many of the presently known distillate fields should operate for many years and prevention of corrosion of the steel equipment is essential if operating costs are to be kept at the lowest possible figures during the life of the field. Under present wartime conditions, proper maintenance of this steel equipment is even more important than in normal times.

External corrosion of steel equipment in the distillate field is entirely normal, may be detected in the usual way, and may be protected against, using methods identical with well-known methods that have been perfected for low-pressure gas and oilfield equipment protection. There is a possibility that internal corrosion in the high-pressure distillate field may differ materially from internal corrosion previously observed in operations conducted at lower pressures. We have recently obtained some information regarding one case of rather unusual internal corrosion in a distillate field that might be of some interest if other similar cases are found in the industry.

The Lone Star Producing Company operates three distillate recovery plants at present. The Grapeland Plant has been operated for about three years, the Opelika Plant has been operated for about two years, and the Willow Springs Plant has been operated for a little more than one year. These plants produce from 1 to 2 bbl. of liquid water per million cubic feet of gas processed, and this water is removed from the gas stream in the inlet separators at the plants. The dissolved iron content of this water is appreciable at all three plants, and will range from 200 to well over 1000 parts per million of iron. This dissolved iron, may, of course, be present in connate water produced with the gas or may be dissolved from the iron equipment used to convey the gas from the formation to the plant. It appears that at least some of this iron has been dissolved from the gathering systems in all three plants.

The wellhead fittings have been inspected internally at all three plants. Fittings at Grapeland show some pitting, well distributed over the internal surface of the various pipe and fittings with no serious reduction in strength of these items. Internal inspection of wellhead fittings at Williow Springs shows some removal of metal with a fairly smooth surface left and with well distributed metal removal, so that the items are not materially weakened.

Internal corrosion at Opelika is very different from that at Grapeland and Willow Springs as shown by visual inspection. Serious and highly localized corrosion of the internal pipe surfaces occurs immediately downstream from the various fittings and orifice plates as a rule, and straight runs of pipe are corroded only slightly. Fig. 1 shows an example of this corrosion at Opelika. The rate of corrosion at Opelika is sufficiently great to cause condemnation of some fittings after only 90 days' service. Cast-steel fittings and valves appear to be especially susceptible to this corrosion.

The gas at Opelika has been examined for constituents that might be corrosive. Carbon dioxide is present to the extent of about 1 percent by volume. Traces of hydrogen sulphide are also present, but test results indicate that the hydrogen sulphide concentration does not exceed 0.1 grains per 100 cu. ft. The water produced with the gas contains less than 1000 parts per million of chlorides, and less than 1500 parts per million of total solids, so is a very dilute salt solution. The pH of the produced water is from 5.0 to 6.0 at the well. No other corrosive compounds have been identified.

The serious nature of the corrosion at Opelika was first observed in September, 1942. Preventive work was begun the latter part of December, 1942. This work at present involves some correction of the pH value of the produced water by injection of soda ash solution into the gas stream at the well. The Opelika wells are produced through tubing only, in all cases. A solution of ½ lb. of soda ash per gal. of water is pumped down the casing at a rate of approximately 2 gal. of solution per million cu. ft. of gas produced.

The water samples obtained at the wellhead show pH values ranging from 7.0 to 8.0 after injection of soda ash, and chemical tests indicate iron contents of water samples at the wellhead

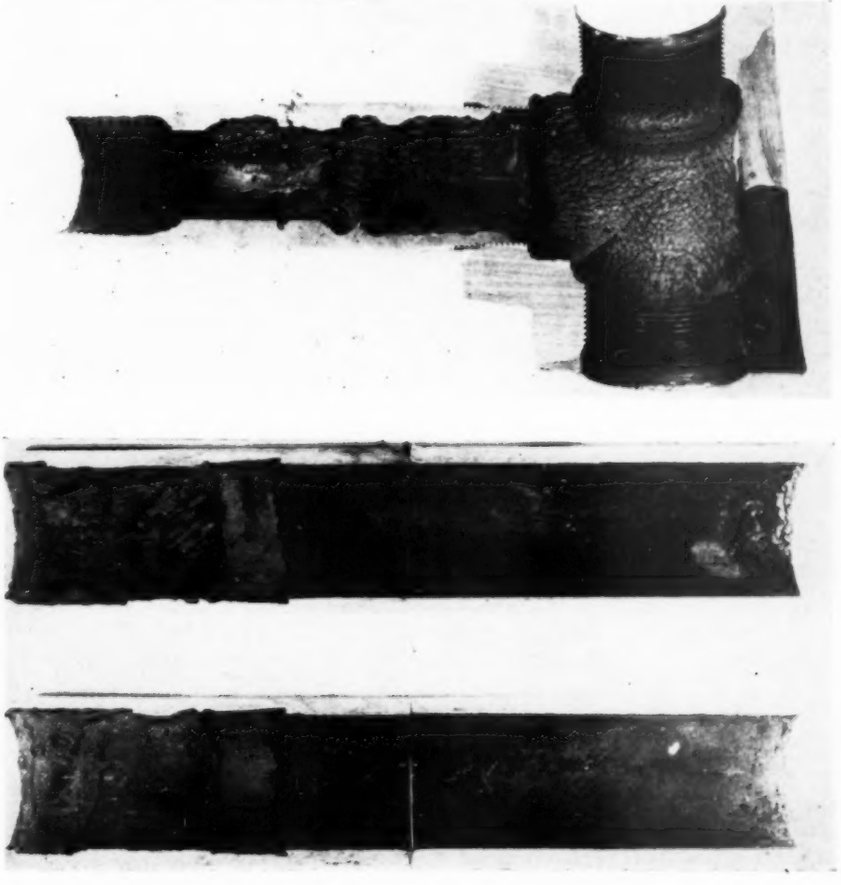

Fig. 1. Examples of corrosion at Opelika

*Presented before Natural Gasoline Association of America, Annual Meeting, Dallas, Texas, April 14-16, 1943.

ranging from 5 to 30 parts per million. In this connection, water samples obtained at the wellheads without soda ash injection showed iron contents of from 150 to 300 parts per million. Visual examination of the wellhead fittings is not conclusive at present due to the relatively short time of soda ash injection. A cast-steel cross shows slight corrosion after two months of service on a well protected by soda ash injection. It is believed that this corrosion is materially less than would be expected in the absence of soda ash. A small, single-acting, plunger pump driven by a gas-actuated diaphram is used to pump the soda ash solution into the casing. The gas required to drive the pump is obtained from the flow line from the well. Some mechanical trouble has been experienced with pump valves and packing in this service, and pump maintenance has required an excessive amount of field labor. Slight changes in the mechanical design of the liquid ends of these pumps are being made, however, and it appears that these changes have increased the reliability of these pumping units.

It is possible that some corrosion inhibitor might be used, either alone or in conjunction with the soda ash solution, to give better results. We have not investigated the possibilities of inhibitors in this connection to any appreciable extent to date. Some form of electroyltic protection, such as the insertion of zinc plugs in the internal pipe surface, has been suggested, but no experimental work has been done by us on this method of protection.

Tubing was pulled on one well and was found to be in almost perfect condition with only slight signs of attack on the bottom of each joint of tubing, The Christmas tree flange immediately above the tubing was appreciably corroded over its entire internal surface, and the master tubing gate was badly corroded. This examination indicated that corrosion started immediately on leaving the tubing and reached its maximum intensity at this point. A complete examination of the internal surface of the field line is, of course, impossible, but examination of the plant end of the field line showed negligible corrosion. No corrosion has been observed in the plant itself.

The Opelika distillate field presents an important maintenance problem at present due to internal corrosion at the wellheads. We feel that we have arrived at a partial solution of this problem, but that there is much still to be learned both as regards the cause of this corrosion and as regards the cure. Cooperative effort on the part of the industry should assist in solving this problem and would be of value in the conservation of critical materials.

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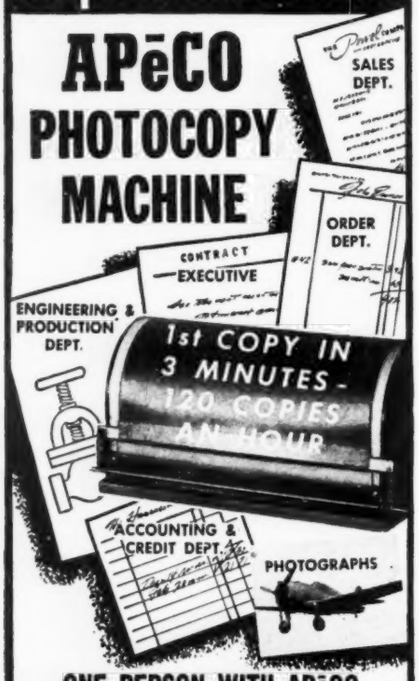

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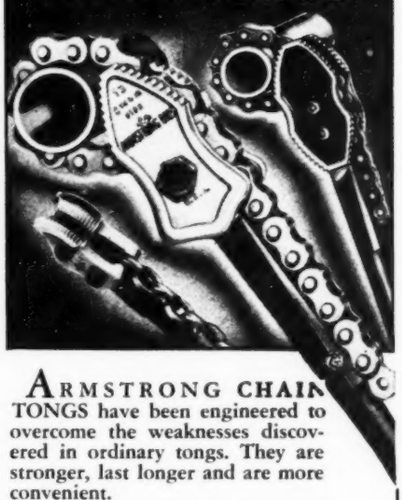

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The Problem of Increasing Recovery*

By

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Abstract

INCREASING war demands for additional production of crude oil coupled with the scarcity of materials used in drilling new wells necessitate greater emphasis upon increasing recovery by improved techniques. Several factors relating to improved recovery practice are discussed. Recent improvement in California production practices is reviewed. Need for pooling the knowledge and experience of all operators is stressed, as well as the need for further research. The paper concludes with a statement that the problem of increasing recovery is a practical one which pays off in dollars and cents, and that its solution is a "must" during war.

Introduction

For many years the problem of increasing the ultimate recovery of oil from a reservoir has been receiving widespread attention by the entire oil industry. This attention is well justified, as there are few ventures that offer the same possibilities of financial return. Consider the oil reserves of California—somewhat in excess of 3,000,000,000 bbl. If production practice could be improved to effect but a 1 percent increase in recovery, 30,000,000 additional bbl. of oil would reach the stock tanks. A 10 percent increase would result in 300,000,000 additional bbl., a figure comparable with the reserves of the largest fields in California. From an economic viewpoint, the picture is attractive, particularly since the wells are already drilled.

The war has had a pronounced effect upon the oil industry. Scarcity of materials has forced curtailment of drilling, whereas product demand resulting from all phases of increasing war activity has skyrocketed upward. To meet this sustained war demand in face of reduced drilling, it is imperative that the oil industry concentrate upon the problem of increasing recovery and redouble its efforts to provide the most effective solution.

Selection of the best procedure for producing a reservoir presents many complications. Performance characteristics vary widely among reservoirs, and the production procedure should be adapted to the particular reservoir in question. Even then, well-qualified engineers may disagree upon some details. Certain general policies, however, are agreed upon by most, if not all, engineers, and it is proposed to review these at this time.

*Presented before American Institute of Mining and Metallurgical Engineers, Los Angeles, California, October 15 and 16, 1942.

Reservoir Expulsive Forces

It may be well to look at an oil and gas reservoir from an energy standpoint, and see what forces are available for the expulsion of oil. They may be simply listed, as follows:

This paper was the introductory one of a symposium on "Recovery as Affected by Production Techniques," and, although it is a general discussion of the subject, presents some timely and pertinent suggestions on oil recovery problems in California.

1. Water drive. The accumulation history of an oil reservoir demands, almost without exception, that it be wholly or in part in contact with a water body existing initially at the same pressure. Geology and lithology of the area may limit the size and effectiveness of this water body, but it usually represents a tremendous external source of energy which may be used to force oil to the well bore.

2. Gas expansion. All oil reservoirs contain some gas dissolved in the oil, and many possess initial gas caps in contact with the oil. In the deeper reservoirs, the initial energy of the dissolved gas alone is many times greater than that required thermodynamically to produce all the oil from the reservoir. Internal and external gas drive provides a major expulsive force.

3. Gravity. The gravitational field of the earth provides an always-existing force aiding the production of oil. Its relative effect is usually slight during the early history of a reservoir, but when depletion has reached an advanced stage, gravity may constitute the major extractive force. Gravity is most effective in fields of high permeability and where thick sand sections and steep dips are encountered.

All the above forces are natural, but energy may be added artificially to the reservoir. Fluids, usually gases, can be injected into the reservoir during its early productive life to provide primary pressure control. The process of holding the reservoir pressure essentially constant by fluid injection is known as pressure maintenance.

Fluid injection into a reservoir that has reached its economic productive limit under application of naturally occurring forces results in secondary recovery or recovery by secondary pressure control.

Production Practice and Recovery

The problem of increasing recovery resolves itself into finding methods for more efficient use of the natural energy available in or to the oil reservoir or in adding additional energy from an external source in an artificial manner. Unlike the object of a laboratory experiment, an oil reservoir, having a given number and configuration of wells, can be reached only through these wells. By means of well completion or recompletion, the degree of contact that any well makes with the reservoir can be selectively controlled to include desired oil-producing horizons and to exclude undesired water and gas. Withdrawals from a reservoir produced by natural forces then form the sole measure for control, and two degrees of freedom are possible; i.e., rate of production, and areal distribution of production. If energy be added to the reservoir from an external source, an additional control is provided through selective injection.

In discussing the actual production mechanics that should lead to high ultimate recovery, it is proposed to center the treatment around those procedural principles that are generally accepted by the petroleum engineering profession. Perhaps these may be listed as follows:

1. Maintain reservoir pressure above the bubble point, or, at least, at its practicable maximum.
2. Produce with a minimum gas-oil ratio.
3. Favor production at a low rate.
4. Produce with a minimum water-oil ratio.
5. Maintain a uniform or balanced pressure pattern throughout the reservoir.
   (a) To avoid pressure sinks.
   (b) To prevent uneven edgewater encroachment.
   (c) To avoid gas-cap contraction.

The above factors are fundamental but interrelated, and they could be stat-

ed in other forms through recombinaervoirs in the same manner, as there is a wide variance among reservoirs in structure, lithology, kind, and distribution of hydrocarbons, and availability of energy per barrel both as to kind and tion. They cannot be applied to all resamount.

Before proceeding further, it might be well to examine what takes place when a reservoir is abandoned or becomes a candidate for secondary recovery. If an effective water drive has been enjoyed, abandonment comes with the complete flooding of the producing horizon. The more usual condition at the end of the primary recovery life, however, is that insufficient energy remains to force oil into the well bores at a sufficient rate to make production economic, although a high percentage of the oil originally in place still exists in the reservoir. A convenient way to visualize this endpoint condition lies in consideration of the final oil saturation. The final oil saturation, and the consequent effective permeability of the producing sand to oil, are so low that the pressure differential between a remote point in the reservoir and a well bore is insufficient to flow oil of the existing viscosity into the well bore at a commercial rate. Conversely, it may be reasoned that the economic productive life of a reservoir may be increased materially by maintaining a lesser oil viscosity. Although it is dangerous to generalize too widely on the relationship between pressure and viscosity, it may be stated that saturated oil viscosity often doubles or trebles when the pressure is reduced to 5 or 10 percent of the initial value.

Laboratory flow data indicate a decreasing effective oil permeability with decreasing oil saturation. For a constant water saturation, however, the oil saturation must vary inversely with the gas saturation. Hence, for a sand throughout which it is desired to retain a maximum oil permeability, a minimum gas saturation must be maintained. This argument may appear specious, as a high ultimate recovery of oil can only be obtained by a relatively low residual oil saturation. Nevertheless, one may draw two pertinent conclusions: First, that gas is a more effective expulsive agent when it expands progressively through an oil sand, cleaning as it goes, rather than when it flows continguously with the oil throughout the entire section. Second, that the amount of tank oil making up a fixed oil saturation be a minimum. This can be accomplished by maintaining a high pressure, a maximum amount of gas in solution, and a resulting high oil formation volume factor.

Maintaining Pressure

With the above considerations in mind, let us turn to the problem of maintaining pressure in a reservoir. The simplest and cheapest method, when feasible or possible, is to produce at such a rate and with such distribution that the edgewater encroaches evenly, and completely replaces the fluid volumes withdrawn. In this ideal case the pressure is fully maintained, effective permeability to oil stays at a maximum, oil viscosity is held at a minimum, residual oil becomes a minimum, and recovery is maximum. Gas remains effectively in solution in the reservoir, expanding in the well bores to flow the wells possibly to depletion without artificial lifting equipment. It must be admitted that the ideal case of complete edgewater drive is far from being universal, but the possibility of taking full advantage of edgewater drive should not be abandoned without full test. A new reservoir should be produced at the lowest rate commensurate with the minimum necessary rate of financial return (except where positive military demand exceeds it) and for a sufficient period of time that the pressure behavior of the resorvoir clearly indicates whether or not it is feasible, or even possible, to produce the reservoir under full edgewater drive. Only when this test has been made, and the edgewater activity found inadequate, should consideration be made of artificial pressure maintenance, or the reservoir produced at a higher rate by gas expansion.

Artificial pressure maintenance, usually by means of injecting at least all produced gas to the formation, permits the attainment of all the benefits of natural water drive with the exception of the flushing effect of water. In addition, the rate of recovery may be increased substantially, because, if the pressure be maintained above the bubble point, the theoretical limit on production rate hinges on the capacity of the gas injection plant. The costs, however, are higher, and difficulties arise in the prevention and control of gas bypassing with the consequent recycling of excessive gas volumes. On the other hand, the stakes are high, for authorities believe that by artificial pressure maintenance recoveries will exceed those from depletion drive by up to 50 and possibly even 100 percent. In addition, and this is particularly true for the deeper reservoirs, the cost of a pressure-maintenance installation may be no more and possibly even less than the cost for artificial lifting equipment if the pressure is allowed to decline to a low level.

If edgewater activity has been weighed and found wanting, and if a pressure-maintenance project has not been found possible, due either to lack of unified control, financial unwillingness, or current scarcity of critical materials, it is necessary to produce the reservoir by gas expansion or depletion drive. Many older reservoirs, not in the latter stages of their productive lives, likewise fall into this grouping. Some may have had no appreciable water drive; others, however, have been produced in the past at rates exceeding the ability of the edgewater to move in and replace the volumes withdrawn. This has resulted in pressure reduction and consequent gas expansion. It now remains to discuss the best production procedures to follow under depletion drive.

Minimum Gas-Oil Ratio

It is generally agreed that a reservoir produced by gas expansion will release the great majority of its gas, which will be recovered regardless of the specific production procedures followed. That is, the volume of recoverable gas tends to be constant. It immediately follows that the lesser the ultimate accumulated gas-oil ratio, the greater will be the oil recovery, and, as a corollary, any production practice that will result in oil production at a lower gas-oil ratio will tend to increase the ultimate recovery of oil. This is the second "axiom" on the list.

There are several methods to reduce production gas-oil ratio, and all should be tried. Well completion or recompletion to exclude gas producing sands is among the most important. Squeeze cementing and the use of packers form appropriate methods if a cemented string lies across the gas producing interval. Selective well production is another powerful method. Possibly the method that has been most overlooked can be of greatest value — that of studying pool performance with rate. As production is taken from a pool having ineffective water drive, the gas-oil ratio is bound to go up as the pressure falls below the bubble point. The rate of increase of gas-oil ratio in terms of accumulated oil produced is usually a function of production rate, however, particularly so in reservoirs of low permeability. A careful study of this relation should be made to determine a maximum rate beyond which the reservoir should not be produced.

Low Production Rate

In the preceding discussion it has been pointed out that a low rate of production may permit taking full advantage of edgewater encroachment and, in the case of a pool under depletion drive, may promote attainment of a minimum gas-oil ratio. Observation of pool performance will result in determining the existence of such effects.

Two other general and beneficial results from low production rates are indicated by theory and laboratory data. First, to avoid trapping of oil in a tight sand lens surrounded by sands of greater permeability when the entire sand measure is subjected to water drive, it is essential that the rate of water encroachment be relatively low, so that capillary forces and the phenomenon of "counter-flow" have sufficient time to expel the recoverable oil from the lens. Water encroachment at too high a rate will cause bypassing of the sand lens before its limit of exhaustion has been reached. Second, in the case of a depletion type pool, or any pool wherein the pressure is below the bubble-point, it may be possible to reduce the gas-oil ratio at a low production rate by encouraging gravity separation of the gas from the oil. If the reservoir has such properties as will permit the gas to accumulate high on structure, and if gas can there be excluded from production, then the energy of such gas can be conserved and used for producing additional oil. It must be admitted that it is difficult to observe these two effects in actual practice, but the underlying theory is sound. Many reservoirs have characteristics that foreclude the realization of these effects. However, this generalization can be made: when in doubt, produce at a low rate.

Minimum Water-Oil Ratio

Closely allied to the maintenance of a low gas-oil ratio is that of maintaining a low water-oil ratio. Any water that enters a reservoir is contributing productive energy, even though the rate of water entry is not sufficient to maintain the pressure. The production of this water through the well bore is a definite waste of energy and should be avoided by early application of whatever cementing technique is indicated, provided that it is physically possible to separate the oil and water production. In sands of low permeability, an added danger lurks. If a well is allowed to produce water as the reservoir pressure decreases, a time will likely come when a short period of well down-time will allow the oil producing sands to be flooded by water from the higher-head water sand. Oil productivity will return if sufficient velocity can be attained to flush out the water and if the well can be economically operated for a sufficient time to accomplish this result. Unfortunate is the operator if this time is measured in geologic units. A common practice is to operate a wet well believed to be approaching a critical condition so that it will not die; i.e., so that its production will be continuously maintained for a maximum length of time. The best solution does not lie in this direction; water should be excluded at its early entrance and prior to its taking control of the well.

Uniform Pressure Pattern

Maintenance of a uniform or balanced pressure pattern throughout the reservoir is closely related to all the above recommended production practices and is a fundamental part of them. Consider the bad effects of pressure sinks. Oil movement occurs solely as a result of a pressure differential, and gas, possessing a much greater fluidity, is tremendously more responsive to differences in pressure. If a pressure sink is allowed to form, excessive amounts of gas come out of solution, and the area of low pressure tends to become an area of high gas-oil ratio. Gas saturation builds up in the low-pressure area, and the effect expands in the direction of increasing pressure. Gas and oil move toward the pressure low; greater are the gas volumes than those of the oil due to the lesser gas viscosity and because of the increased permeability of the sand to gas. One effect augments the other and leads to "snowballing" so that great gas volumes soon are moving over considerable distances. The overall effect is deleterious to recovery for two immediately apparent reasons; first, gas is "robbed" from distant areas, thereby needlessly removing energy that should be used for production of oil in those areas, and second, the increased permeability to gas must result in a decreased permeability to oil, a lowered productivity index, and a lesser oil recovery in the low pressure-high gas-oil ratio area.

To obtain an even edgewater encroachment in a field it is necessary to avoid uneven pressure distribution around the perimeter. If a localized low-pressure area is allowed to form near the edge of a pool limited by edgewater, fingering of this water is bound to result. Particularly in tight sands, the production of water is likely to restrict oil productivity, and, in any event, the premature incursion of water is likely to reduce recovery. If two adjacent water fingers are allowed to coalesce, the oil trapped in between is subject to complete loss unless a well exists or can be drilled within this area.

One of the most important reasons for pressure control lies in the prevention of oil migration into a gas cap. Laboratory data show that oil that moves into a gas cap wets the "dry" sands and becomes unrecoverable to the extent of 50 percent or more. Wanton production of gas-cap gas is wasteful from the standpoint of needless loss of propulsive energy, as well as allowing oil to be drawn into the gas-cap area and there to become largely unrecoverable.

Pressure Distribution Control

A word or two may not be amiss on the production procedures involved in the control of pressure distribution within a reservoir. Obviously, systematic subsurface pressure measurements must be made in a periodic manner. By studying the pressure distribution in plan, it is possible to determine in a rough way a method for selective production to reduce any pressure unbalance existing in the reservoir. A more precise and effective procedure is to distribute production according to a formula that relates properties of each well in such a manner as to reduce existing pressure differentials or to prevent their occurrence. One formula now in common use involves a sand volume factor, a spacing factor (if spacing is not uniform), a pressure correction factor, and a formation volume withdrawal factor. Various adaptations are used, involving relative weighting of these factors, and some formulae introduce structural position and well productivity index as added parameters. No one formula can be applied to the best advantage of all reservoirs due to varying physical characteristics and problems of equity that arise from diversification of property ownership and operation. In every case, however, the effectiveness of any formula can be checked by the results which accompany its use.

California Practices

During the last year tremendous strides have been made in California toward the goal of achieving a maximum practicable ultimate recovery. Under the direction of Recommendation 19 maximum efficient rates have been determined for all pools. For each critical field, the maximum efficient rate has been determined by a group of competent engineers from the ranks of the industry who have collected data and made detailed engineering studies. Unless so required by a specific war demand, no pool is produced in excess of its maximum efficient rate. Other beneficial work of this engineering committee includes the determination of minimum efficient rates for some pools designed to minimize energy loss by regional drainage or to prevent oil encroachment into gas-cap areas.

Much can be said for the improvement in intra-pool allocation procedure. A year ago practically all intra-pool allocation was based purely on well depth and well capacity without regard for conservation of reservoir energy and pressure distribution. In all fairness, however, it should be stated that several operators were following practices for minimizing waste and increasing recovery, but a universal appreciation of the problem had not been attained.

This may be contrasted with the present situation wherein for September, 1942, twenty-three critical fields are receiving well allocations based wholly or in part on formulas devised for the purpose of conserving energy and increasing ultimate recovery. Many other pools, controlled by a multiplicity of operators, are not allocated according to a basic volumetric formula, but for the large part, are operated according to sound engineering principles.

Independent action on the part of individual operators has resulted in many cases of improved production practice. In one instance, four operators banded together to buy out a gas-cap operator, shut in gas-cap production, and take advantage of pressure maintenance by natural water drive. At the time of writing, two pressure-maintenance projects are going into operation to provide complete return of produced gas, thus marking a milestone in California production practice. Several other projects are now operating to provide partial return of produced gas, and one in particular has shown remarkable results in allaying pressure decline and in improving recovery efficiency. The Paloma field, subject of last year's symposium, is being produced with nearly complete gas return from a pilot plant installation, although construction of a full sized plant has been delayed pending the obtention of sufficient priority to enable the purchase of the requisite scarce materials.

Future Study and Research

Perhaps the outstanding achievement of the California oil industry has been its willingness to coöperate in the common problem of providing the necessary oil of the proper kind to meet the specific war demand. In the interests of providing information to and the study of maintaining an adequate future supply of oil, the industry has broken many time-honored shibboleths and pooled data previously regarded as secret. This response has been laudable, but we are far from the ultimate that can be obtained. The progress made during the last year must be enlarged upon. A field or pool can be best studied by those who operate it and who know it best. The establishment of field engineering committees to conduct detailed studies is to be recommended. From such work there is much to be learned, and much of a beneficial nature to be accomplished. Through a full concept of the performance of a pool as a whole, the ever-occurring and difficult problem of equity arising from diversified ownership can be approached on a rational basis to the end of establishing satisfactory operating agreements and even full unitization. Results of independent and varied research projects should be pooled for the common good. The services of the A.I.M.E. and the A.P.I. in meetings like this are invaluable in providing a means for disseminating such information. Additional research is indicated. A coöperative venture—jointly sponsored—provides an effective approach, but independent research should likewise be stimulated. A major portion of current knowledge of reservoir behavior has been developed during the last decade alone, and the path for increasing this knowledge is an open one which lies directly ahead.

Conclusion

I should like to leave this one thought in your minds. The problem of increasing recovery is not one of pure theory. It is a practical one that pays off in dollars and cents. Current production practice probably leaves behind an average residual oil representing 70 percent or more of the oil originally in place. Recovery of an increasing fraction of this oil presents a challenge to the engineering talent of the industry. During normal peace-time conditions this challenge should not go unheeded; it is a "must" during war.

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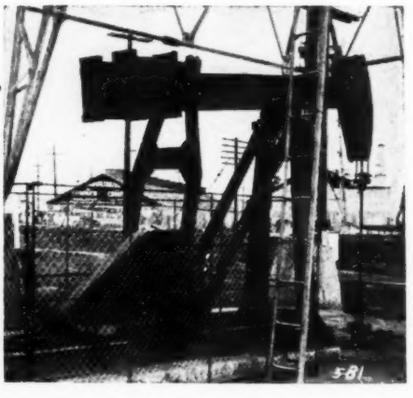

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P 532.1

Reconditioning Wells in the Gulf Coast Area*

By
C. E. REISTLE, JR., and T. A. HUBER
Humble Oil and Refining Company

RECONDITIONING wells is a term that includes such a wide range of operations that it is doubtful the entire subject could be covered in a single paper of reasonable length. For the purpose of this paper, reconditioning wells includes the following: (1) changes in the mechanical setting of a well or the amount or location of the formation exposed for production, but excluding changes in artificial-lift settings, ordinarily known as workovers; (2) increasing the effective permeability of the producing formation adjacent to the well, such as acidization and nitroglycerin shooting; and (3) simple clean-out work, such as sand bailing and paraffin removal. This paper will be limited to a discussion of some of the more important developments in workovers.

Possibly it would be well to indicate at the outset the differences between Gulf Coast reconditioning work and workovers in other areas. In this area, the average depth of wells is much greater than the average for most other important producing areas, and this requires that regular drilling rigs be used in a large percentage of workover operations at a greater expense than is experienced when portable equipment may be more generally utilized. The average workover cost is somewhere between $8,000 and $12,000 per well, whereas, the average workover cost in all other areas will run in the neighborhood of $3,000 to $4,000 per well. Another factor of importance in this area is that the majority of the fields have their reservoir energy supplied principally by water drive. This tends to make reconditioning operations predominantly of the workover classification, there being only a minor portion of the work performed to increase the productivity of marginal wells. The diagnosing of well troubles and prescribing corrective operations are of great importance as records indicate that 30 to 40 percent of workover jobs are unsuccessful. The cost of reconditioning wells amounts to 10 to 20 percent of lease-operating expense.

Developments in the mechanical aspects of working-over wells have been chiefly along the lines of perfecting principles that have been used for some time. Of main interest is the continued application and development of squeeze cementing, gravel packing, and portable equipment for deep operations.

Possibly of most importance and greatest interest in reconditioning work in this area is the tendency in recent years to give a great deal of attention to its reservoir-economic aspects. Developments along these lines have come about principally as a result of: (1) greater knowledge and experience in interpreting reservoir performance, (2) utilization of methods for obtaining more and better information on the producing formations, such as electric logging, core analysis, mud analysis, and caliper logging, (3) better records both of equipment and well and reservoir behavior, and (4) the decline in well allowables has made it necessary to give serious consideration to the economic aspects of each individual workover.

In determining the type of workover that shall be performed, the manner in which wells were originally completed is important. The setting of pipe into or through the producing formation and perforating it for production has been popular for a number of years, and these completions are now being worked over frequently. One variation of this type of completion, where the producing sand is reasonably thick and well consolidated, consists of setting pipe a short distance from the final completion depth and producing from the open hole. The thought in this case is that the well will be plugged-back to the casing and the casing perforated for additional production after the lower portion of the producing formation has been depleted. In these types of completion where the pipe is set into the formation, the workover job is usually simplified in comparison with operations where the oil string is set above the producing formation; however, caution must be exercised in regard to hole diameters wherever pipe is cemented in the formation, because experience indicates that ordinary gun-perforating does not penetrate formations beyond a thickness of 4 or 5 in. of cement behind the pipe. If consideration is not given to this factor, productive formation may be cased off entirely in the particular well. It might be pointed out also that caliper surveys have shown a tendency for sand formations to maintain fairly well their drilled-hole diameters, and this is also confirmed by the fact that little difficulty has been had in bringing wells into production by gun-perforating.

Diagnosing Well Trouble

When a well gives indication that it will require working over, the diagnosing of the trouble may be done in two steps, as follows: (1) a preliminary survey of performance information, and (2) a detailed study of well completion and reservoir characteristics. Prior to any diagnosis of well problems, an understanding as to the location of the well in regard to the various structural and reservoir features should be obtained.

Sometimes a preliminary investigation indicates that the well can be very economically worked over, and that it is unnecessary to make a more detailed study. For instance, the preliminary check-up of water analyses and operating data may show casing leakage into or out of the well and indicate that an inexpensive packer setting or other method can be used to shut off such leak. On the other hand, the well-performance record may show that after a time the water percentage increased rapidly and remained at a certain high percentage for a long period of time, and this, used in conjunction with a knowledge of the formation characteristics, may indicate the water to be produced from a relatively thin but highly permeable section that contained only a small percentage of the recoverable oil available to the particular well. If the workover requirements are not indicated by the preliminary analysis, it is then necessary to consider a more complex analysis that involves a study of the well completion, the reservoir, and the economic aspects of a possibly more costly job.

In the case of free-gas production, it might be pointed out that the wells in this area are generally penalized in oil allowable for the production of gas in excess of 2000 cu. ft. per bbl. Usually, it is but a fairly simple matter to make a preliminary diagnosis of the reason for free-gas production. In the water-drive type of reservoir where the pressure is maintained at a fairly high percentage of the original pressure, the free gas can come only from the gas cap by coning down through formation of good continuous vertical permeability, by flowing down around the casing because of a poor cement job, or by displacement of the oil from an intermediate and highly permeable sand connected with the gas cap. The same would be true for the production of free gas from a reservoir produced by an expanding gas cap prior to the liberation of solution gas that occurs only after a considerable

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drop in reservoir pressure; however, in the case of a dissolved-gas-drive field, some knowledge must be had of the liberated solution gas that must be produced as free gas with the oil at any particular stage in the life of the reservoir in order to determine whether or not there is excess gas coming from a secondary gas cap or from the upper part of the producing formation that may be sealed off to advantage.

Reservoir-Economic Aspects

Usually, workover operations do not become necessary until the reservoir has been well defined and its characteristics have been determined. Most frequently, reservoirs are developed on the basis of what is urgent or required at the time and with a minimum of desirable information regarding how any particular well will fit into the overall producing of the reservoir. At the time such wells are worked over, it is very often possible to fit them into the overall producing picture better than they had been on initial completion, because of the increased knowledge of reservoir and formation characteristics when workovers are required. At such time, consideration should be given to the possibilities of recompleting the wells in the various reservoirs so that the largest possible number of wells will produce for a maximum period to the end that all reservoirs and wells may be depleted at approximately the same time; otherwise, the disregarding of proportional withdrawals from each reservoir may result in having to produce the field over a greater length of time and at a greater overall operating cost. Naturally, the rate of withdrawal must be kept within the limits of efficient recovery; however, in this area most reservoirs and wells are produced at rates considerably below the maximum at which they can be efficiently depleted. This being the case and with the well having considerable importance in the allocation of production, the operator will usually attempt to keep as many wells on production as possible and at the least operating cost.

After consideration of the proration factor and the operating costs, it is desirable to look into the relation of reservoir performance and the types of recompletion that can be made. For a water-drive type of reservoir, the degree of maintenance of reservoir pressure will indicate the part of the zone in which the well may be recompleted so that gas-cap free gas and bottom water will be excluded for an economic maximum length of time, which must be considered in conjunction with the character of the formation and the probability of effectively draining the reservoir by either the recompleted well or an upstructure well. For the dissolved-gas-drive type of reservoir, workover operations will ordinarily be performed to exclude some free gas that may be forming a secondary gas cap or to deepen the well so as to take in more of the oil productive section. The ideal recompletion under this type of drive is one that extends to the bottom of the producing section. For an expanding-gas-cap-drive type of reservoir, recompletions may be very similar to those for the dissolved-gas-drive type of reservoir and will be performed for the same reasons. The considerations regarding the type of drive effective in the reservoir must also be reckoned with in attempting to increase a well's production by increasing the section open to production.

After the various possibilities of working a well over have been determined, the next step includes the estimating of the value of the production that is likely to be recovered by the recompletion. The cost of the recompletion and the value of additional production must be balanced against several other possibilities. In some instances it may be more economical to continue producing the well in its present condition because the characteristics of the reservoir are such that upstructure wells may not be in a position to drain reservoir lenses that may be shut off in workover operations. Also, if a reservoir has good pressure maintenance and is being produced below a rate that will satisfactorily maintain its pressure, it may be more economical and result in greater ultimate production to continue producing the well with a high water percentage, particularly if the water can be disposed of conveniently at low cost. The economics of handling salt water frequently determines the time at which wells will be worked over. It is becoming necessary to dispose of nearly all oilfield waste water in this area by underground injection, and such disposal runs into a considerable item of operating expense compared with past practices of disposing of salt water by releasing it to streams. This condition is brought about by increased use of stream water for domestic and manufacturing purposes, in addition to the increase in the number of oil fields and amount of oilfield brines being produced. If the handling of salt water is not a particular problem and if its production does not create reservoir waste, it may be possible to avoid or to reduce the number of workover operations in a profitable manner by the use of small tubing, which will permit the continued flowing of wells that are producing with high water percentages in fields where the reservoir pressure is well maintained.

After the possibilities of working a well over and the economics of its recompletion have been considered, it is then advisable to check into estimates and predictions made for wells already recompleted in a particular reservoir, and to alter future predictions and estimates on the basis of the case histories of such wells.

Types of Workovers

For this area, nearly all types of workovers are used to some extent but it appears that the most frequent types of workover operation for the various well problems are as follows:

Purpose	*Type of previous completion*	*Type of workovers*
Exclude water	Cemented and perforated pipe	Perforate, retainer squeeze, and reperforate; perforate, bradenhead squeeze and reperforate; set hook-wall packer
Exclude water	Open hole	Open hole squeeze; set and cement liner and perforate; set formation packer
Exclude free gas	Cemented and perforated pipe	Squeeze cement, reperforate
Exclude free gas	Open hole	Set liner, squeeze cement and perforate; squeeze cement above casing seat, recomplete
Sand trouble	Cemented and perforated pipe	Reset screen; set or reset gravel-packed screen
Sand trouble	Open hole	Reset screen or gravel-packed screen; underream and gravel pack
Increase production of oil	Cemented and perforated pipe	Open additional zones; clean perforated and screening mechanism by acidization or replacement
Increase production of oil	Open hole	Open additional formation; clean or gun perforate screening mechanism in place or replace it

Acknowledgment

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Analysis of Reservoir Performance*

By

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Abstract

THROUGH the use of pressure and production records, formation properties and bottom-hole sample data, the performance of an oil reservoir may be studied analytically to define and evaluate the natural forces acting on and within the reservoir. Use is made of material-balance methods and the equations for natural water encroachment to estimate reserves. Methods for calculation of pressures are given.

A study of the Jones sand, Schuler field, Arkansas, has been made and is given here to illustrate the value of the methods discussed.

Introduction

With the decreasing rate of discovery of new oil reserves, attention is necessarily focused on the efficient development, evaluation, and production of existing reserves. From the nation's viewpoint, the necessity of conserving resources is obvious. From the operator's viewpoint, the problem is to lengthen the period of profitable operation, in an attempt to increase the return on his investment. To do this the operator must take advantage of the natural forces acting on and within the reservoir. Natural water encroachment, the nemesis of profitable operation in the past, can be and is being harnessed to produce a greater oil recovery during the stage of flowing production. Proper evaluation of water encroachment rates and a fuller understanding of reservoir behavior dictate the appropriate production procedures.

Complacency in hit and miss production is obsolete. Oil production must and will approach the efficiency of other businesses, such as manufacturing. A manufacturer will not place an article on the market until he has fully investigated the processes involved, additional investment in equipment, costs of production, and expected profits. These may be modified by actual experience at a later date, but at least he begins with an idea of expected return. It is just as logical that an oil operator should investigate these same factors during the development and the early period of production of an oil reserve.

The complexity of the problems existing in oil reservoirs should not be underestimated. Conversely, they should not be regarded as insoluble. Many completely defy solution, but there are others that can be solved completely or attacked intelligently to yield approximate results.

The petroleum engineer has many tools, both figuratively and literally, at his disposal. Physical data such as core analyses, electrical logs, bottom-hole sample analyses, and bottom-hole pressures are accumulated extensively. Advances in the analytics of fluid flow have kept pace with the advances in measurement of physical data. It is the purpose of this paper to show how some of these records may be analyzed to define certain phases of reservoir behavior.

Material-Balance Methods

Material-balance methods have been ably discussed in the literature.[1-4] Many have used these to good advantage, for them much of this paper will seem repetitious. Others, however, have been reluctant to accept these methods fully, believing that the necessary assumptions of either equilibrium or differential liberation of gas from the reservoir oil limit their quantitative application. It has been found from usage that the differences resulting from the two assumptions are minor and may be considered insignificant.

The general equation derived by Schilthuis[1] is as follows:*

$$\Delta n[u + (r_u - r_o)v] + z = n\left[(u - u_o) + mu_o\frac{(v - v_o)}{v_o}\right] + Z$$

With gas or water injection, it is sometimes convenient to express the equation as:

$$\Delta n[u + (r_u - r_o)v] + z = n\left[(u - u_o) + mu_o\frac{(v - v_o)}{v_o}\right] + Z + Gv + Z_i$$

In this form, the left side of the equation is the reservoir volume voided by production. The right side contains the volumes that must fill this void; namely, expansion of oil content and gas cap, water encroachment, injected gas and injected water.

The terms Δn, r_n, z, G, *and* Z, represent volumes obtained from field production and injection records. The terms u and r_0 are determined from bottom-hole sample analyses. Values of v can be determined directly from a sample of gas-cap material or can be calculated from its hydrocarbon analysis.[5] If samples of gas cap are unobtainable, a close approximation of the volume v can be made from an analysis of casing gas. The value for m can be determined from core analyses and development records.

Adequate logs and core analyses for porosity and content of connate water will give a measured value of n, the oil originally in place. The cumulative water encroachment Z can then be calculated directly. However, in many of

*Nomenclature at end of paper, preceding references.

[1]References are at the end of the paper.

*Presented before American Institute of Mining and Metallurgical Engineers, Austin, Texas, October 29-31, 1942.

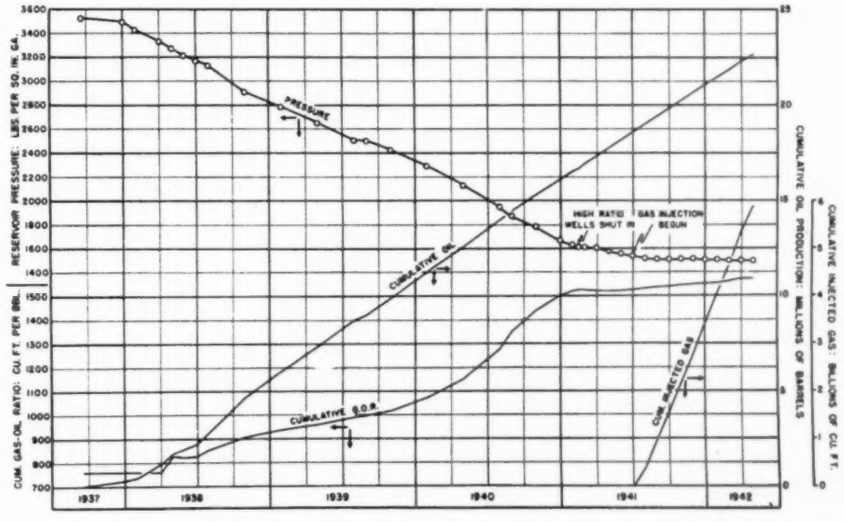


Fig. 1. Pressure-production history of Schuler field, Jones sand

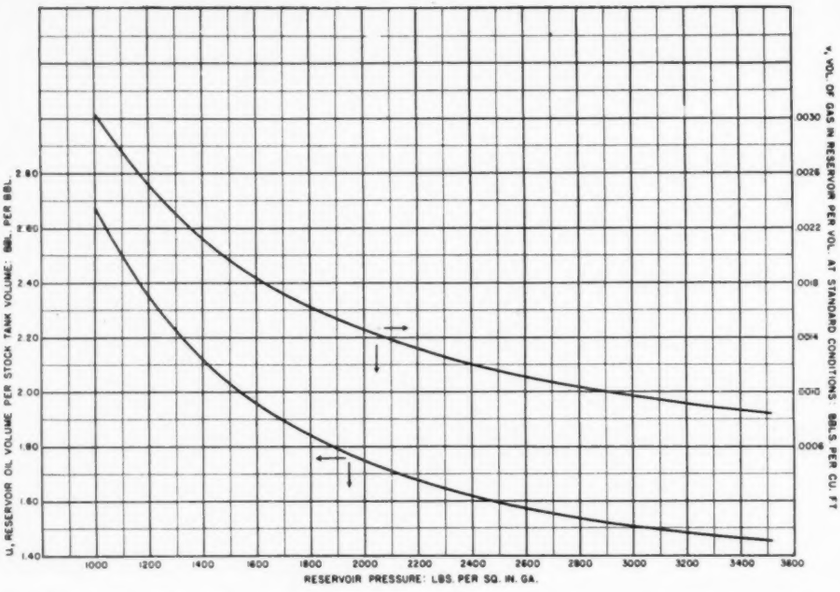


Fig. 2. Variation of reservoir fluid properties as a function

the older fields where these data are incomplete, n may be estimated or calculated by material-balance methods.

Water-Drive Calculations

The solutions of equations for the unsteady-state flow of water into a reservoir for different geometrical configurations have recently been published by Hurst.[6] The radial-drive equations have proved especially applicable. The equation derived by Hurst for cumulative water influx is as follows:

$$Z = \frac{2\pi(144)K\sigma HR^4}{5.615\mu\alpha^4}\left\{\frac{P_R - P_1}{\theta_1}[\bar{G}(\alpha^2\theta/R^2) - \bar{G}(\alpha^2(\theta-\theta_1)/R^2)] + \frac{P_1 - P_2}{\theta_2 - \theta_1}[\bar{G}(\alpha^2(\theta-\theta_1)/R^2) - \bar{G}(\alpha^2(\theta-\theta_2)/R^2)] + \frac{P_2 - P_3}{\theta_3 - \theta_2}[\bar{G}(\alpha^2(\theta-\theta_2)/R^2) - \bar{G}(\alpha^2(\theta-\theta_3)/R^2)] \cdots + \frac{P_{n-1} - P}{\theta - \theta_{n-1}}[\bar{G}(\alpha^2(\theta-\theta_{n-1})/R^2)]\right.$$

It has been found that the values of α^2/R^2 inside the $\bar{G}$ functions are not critical, and that the calculated water encroachment can be considered a function of pressure change with time. For the sake of simplicity, therefore, this equation will be referred to as:

$$Z = Cf(P, \theta)$$

where:

$$C = \frac{2\pi(144)K\sigma HR^4}{5.615\mu\alpha^4}$$

C must usually be determined empirically in conjunction with the material-balance equation because of lack of complete data on formation properties in the water zone.

In order to illustrate the use of the material-balance equation, the water-drive equation, reservoir formation and fluid characteristics and field pressure and production records, an analysis has been made of the Jones sand, Schuler field, Arkansas.

Schuler Field, Jones Sand

The Jones sand of the Schuler field was discovered in September, 1937. An impressive amount of data has been accumulated during its development and production.

Pressure declined from an original of 3520 lb. per sq. in. to 1600 lb. per sq. in. by February, 1941, when the field was unitized. At that time several wells having high gas-oil ratios were shut in, causing a slower decline. Gas injection was begun in July, 1941. Since that date the reservoir pressure has remained virtually constant at 1500 lb. per sq. in. Water production has been negligible and probably will continue so for several years because of the practice of shutting in wells when they become wet. The pressure and production records are shown in Fig. 1.

Calculations show that there is natural water encroachment into the Jones sand, but its magnitude heretofore has been insufficient to keep pace with the production of oil and gas. Two methods of determining the amount of water influx are discussed in the following cases.

Case 1. Using geological measure of initial oil in place. The Jones sand had an original oil zone of 141,500 acre-feet; an original volume ratio of gas cap to oil zone of 0.037; an average porosity of 17.6 percent and a connate-water content of 35 percent of pore space as determined from the cores of Marcus No. 3. These volumes provide for 125.6 million bbl. of reservoir oil, which corresponds to 86.6 million bbl. of stock tank oil initially in place. The essential fluid properties of the reservoir are given in Fig. 2.

The original oil content, bottom-hole sample data, pressure and production records were used to calculate the cumulative water encroachment Z for different times. The results are given in Table 1, and are plotted versus time in Fig. 3. Up to May 1, 1942, about 13 million bbl. of water has encroached, while the production of 23 million bbl. of stock-tank oil and evolved gas had voided 70 million bbl. of net reservoir volume.

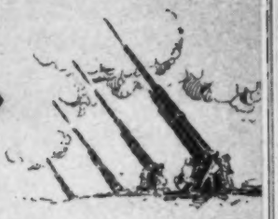
Using the physical constants of $R=6400$ ft., $K=350$ millidarcys, $\Phi=0.176, =2.5(10^{-8})$, $\mu=0.30$ centipoises, with appropriate change in units, α^2/R^2 was calculated to be 0.280. This was used with the pressure-time relations to evaluate $f(P,\theta)$ during the period of production. The value of the function on April 30, 1942, was 54,746, and the cumulative water from the material balance was 13.30 million bbl.; therefore, $C=242.9$. Multiplication of $f(P,\theta)$ by C gives the calculated water encroachments plotted in Fig. 3, which are compared with those calculated by the material-balance equation. The agreement is satisfactory.

Case 2. Using no geological measure of initial oil in place. As there is a mathematical relation expressing the proportional variation in Z as a function of pressure and time, Z and n both can be calculated from the pressure-production records and reservoir fluid properties.

The curve shown in Fig. 4 was determined by assuming different values for C. Calculations for n were made from each of the last 30 pressure-production points for each assumed value. The deviation of n from the mean value in each series was obtained and plotted against that mean value. The minimum deviation occurs where the mean value of n is 86.5 million bbl., indicating that at this point best agreement is obtained between individual pressure-production points.

The value of n the original oil in place, calculated in this manner is 86.5 million bbl. The remarkably close agreement between this value and the geological measure used in case 1 may be fortuitous, but it is indicative of the effort spent in the detailed analysis of sand volume and porosity made by the

HOW AND WHY



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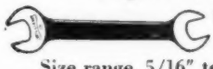


15° Angle, Double Head. For general service.

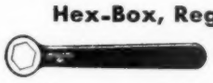
Size range, 5/16" to 5-3/8" openings. Also single head style, 3/16" to 7-5/8".

Check Nut or "Thin" Pattern

15° Angle, Double Head. For Check, Jam or Lock Nuts, etc.

Size range, 13/32" to 1-1/2" openings. Also single head style, 7/16" to 1-11/16".

Hex-Box, Regular Pattern



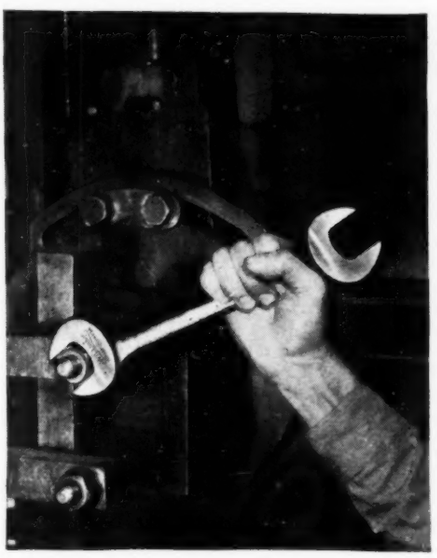
15° Angle, Single Head. For general service.

Size range, 13/32" to 4-5/8" opening. Larger sizes, from 3-3/8" to 4-5/8" opening, are also furnished with *striking face* on end of shorter handle.

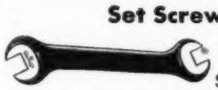
Hex-Box, Heavy Pattern

15° Angle, Single Head. For heavy duty.

Size range, 1-1/4" to 3-1/8" opening. Also made with *striking face* on end of shorter handle throughout full size range.



Set Screw Pattern



22-1/2° Angle, Double Head. For Set Screws, Square Cap Screws & Nuts.

Size range, 3/16" to 1-1/8" opening. Also single head style, 3/16" to 1-1/8".

"S" Pattern

22-½° Angle, Double Head. For Standard Nuts and Cap Screws.

Size range, 5/16" to 2" opening.

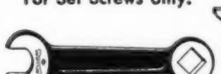
Machine Pattern

Straight Opening. Dbl. Hd. Extra heavy for Planers, Milling Machines, Lathes, Drill Presses, etc.

Size range, 3/8" to 1-7/16" opening.

Tool Post Pattern

For Set Screws only.



For Nuts and Set Screws.

Nos. 554 to 557, for set screw sizes (both ends) 7/16" to 3/4".
Nos. 562B to 568D, openings 5/8" to 2". Same opening both ends.

Heavy "S" or Car Pattern

22½° Angle, Double Head. Long leverage wrenches primarily for railroad use.

Size range, 5/8" to 2-7/16" opening.

Construction Pattern

15° Angle. Straight handle. Deep opening for square nuts, and tapered handle for lining-up bolt holes.

Size range, 7/16" to 2" opening.

Structural Pattern

Straight opening. Offset handle. Deep opening for square nuts, tapered handle for lining-up bolt holes.

Size range, 7/16" to 2" opening.

Face Spanners

For general service.

Size range, 1" to 4" C to C of pins, in 1/4" multiples. Also Adjustable Face Spanners in 3 sizes with 2, 3 and 4" capacities.

Pin Spanners

For general service.

Size range, for circle diameters 1" to 6".

Hook Spanners

For Taper Nose Lathe Spindles and general service.

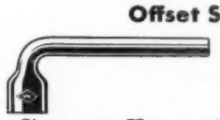
Size range, for circle diameters, 7-3/8", 9-1/4" and 12-1/2". Also Adjustable Hook Spanners in 3 sizes for circle diameters ranging from 3/4" to 4-3/4".

Pin Handle Sockets

With Hex or Square Opening for general service.

Size range: Hex openings 5/16" to 2-3/8". Square openings, 1/8" to 2".

Offset Sockets



With Hex or Square Opening for general service.

Size range: Hex openings, 5/16" to 2-3/8". Square openings, 1/8" to 2".

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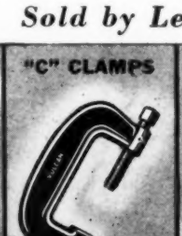


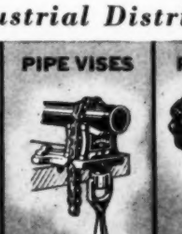


TABLE 1

Material-balance calculations

Date: End of period	Pressure, lb. per sq. in. gauge	Δn, million bbl.	u	$(r_p - r_0)$	$(r_p - r_0)V$	$u + (r_p - r_0)V$	$\Delta n\left[u + (r_p - r_0)V\right]$	G_v	$\left[(u - u_0) + m u_0 \frac{(v - v_0)}{v_0}\right]$	$n\left[(u - u_0) + m u_0 \frac{(v - v_0)}{v_0}\right]$	Z, million bbl.	$f(P, \theta)$
1937—September 17	3,520	0	1.450	0	0	1.450	0		0	0	0	0
December		0.346	1.4525	0	0	1.4525	0.503		0.0030	0.260	0.243	80
1938—January	3.420	0.476	1.459	0	0	1.459	0.694		0.0107	0.927	0.233	192
March	3.330	1.242	1.4675	0	0	1.4675	1.823		0.0265	1.776	0.047	571
April	3.275	1.743	1.4735	69	0.062	1.5355	2.676		0.0274	2.374	0.302	806
May	3.212	1.942	1.480	61	0.055	1.535	2.981		0.0349	3.023	—0.042	1.182
June	3.169	2.222	1.485	67	0.062	1.547	3.437		0.0406	3.517	—0.080	1.349
July	3.125	2.818	1.490	93	0.087	1.577	4.444		0.0464	4.020	0.424	1.926
October	2.910	4.653	1.5173	146	0.146	1.6633	7.739		0.0777	6.731	1.008	3.553
1939—January	2.785	6.030	1.537	179	0.186	1.723	10.390		0.1003	8.689	1.701	5.633
April	2.650	7.360	1.560	200	0.218	1.778	13.086		0.1263	10.941	2.145	7.851
July	2.505	8.751	1.5887	230	0.265	1.8537	16.222		0.1587	13.748	2.474	10.420
August	2.501	9.011	1.5890	237	0.273	1.862	16.778		0.1590	13.774	3.004	11.454
October	2.425	9.873	1.6080	258	0.307	1.915	18.907		0.1805	15.637	3.270	13.458
1940—January	2.290	11.259	1.6454	310	0.304	2.0394	22.962		0.2229	19.310	3.652	14.046
April	2.125	12.619	1.6675	440	0.603	2.3005	29.030		0.2817	24.404	4.626	19.772
July	1.950	13.998	1.766	590	0.825	2.591	36.269		0.3586	31.066	5.263	21.267
August	1.878	14.462	1.801	590	0.920	2.721	39.351		0.3974	34.427	4.924	24.948
October	1.785	15.321	1.8495	640	1.122	2.9715	45.526		0.4515	39.113	6.413	27.930
December	1.670	16.132	1.9150	740	1.310	3.225	52.026		0.5243	45.420	6.606	30.913
1941—January	1.630	16.552	1.940	760	1.383	3.323	55.002		0.5520	47.820	7.182	32.220
February 14	1.609	16.739	1.953	760	1.398	3.351	56.092		0.5665	49.076	7.016	33.359
February 28	1.608	16.929	1.954	759	1.397	3.351	56.729		0.5676	49.171	7.558	34.148
March	1.601	17.348	1.959	756	1.399	3.358	58.255		0.5731	49.648	8.607	35.348
April	1.575	17.757	1.9775	755	1.419	3.3965	60.312		0.5936	51.424	8.888	37.087
May	1.555	18.177	1.9915	756	1.440	3.4315	62.374		0.6092	52.775	9.589	38.675
June	1.537	18.583	2.005	760	1.465	3.470	64.483		0.6240	54.067	10.426	40.194
July	1.514	19.006	2.0225	767	1.503	3.5255	67.006	0.730	0.6435	55.746	10.530	41.443
August	1.505	19.426	2.030	772	1.521	3.551	68.982	1.880	0.6517	56.457	10.645	43.625
September	1.502	19.830	2.033	774	1.525	3.558	70.555	3.010	0.6550	56.743	10.802	44.948
October	1.506	20.249	2.030	777	1.531	3.561	72.107	4.207	0.6517	56.457	11.443	45.123
November	1.506	20.652	2.030	781	1.539	3.569	73.707	5.443	0.6517	56.457	11.807	48.259
December	1.500	21.068	2.034	785	1.551	3.585	75.529	6.722	0.6561	56.838	11.969	49.318
1942—January	1.498	21.474	2.036	789	1.562	3.598	77.263	7.933	0.6582	57.020	12.310	51.097
February	1.492	21.850	2.041	796	1.584	3.625	79.206	9.251	0.6639	57.514	12.441	51.919
March	1.493	22.261	2.040	805	1.602	3.642	81.075	10.730	0.6625	57.418	12.927	53.516
April	1.493	22.619	2.040	806	1.604	3.644	82.424	11.708	0.6628	57.418	13.298	54.740

*$r_0 = 760$; $u_0 = 1.450$; $v_0 = 0.000840$.

TABLE 2

Comparison of calculated and measured pressures after July, 1939

Results plotted in Fig. 5

Date: End of period	Calculated pressure, lb. per sq. in. gauge	Measured pressure, lb. per sq. in. gauge
1939		
August	2489	2501
October	2424	2425
1940		
January	2279	2290
April	2120	2125
July	1946	1950
August	1907	1878
October	1791	1785
December	1685	1670
1941		
February	1624	1608
May	1542	1555
August	1494	1505
November	1492	1506
1942		
February	1486	1492
April	1483	1493

operators in the Schuler field and the Arkansas Oil and Gas Commission. This check also serves to substantiate the connate-water saturation determined from core analysis as well as material-balance method coupled with the unsteady-state water encroachment as a quantitative method for calculating original oil in place.

Pressure Predictions

In addition to defining reservoir mechanics, the material-balance and water-drive equations can be used to predict pressure behavior under different production procedures.

Two methods of handling the mathematics for pressure prediction are possible. One is by differentiation of the material-balance equation and the reservoir fluid properties as functions of pressure. The rate equation for water drive and the balance equation in differential form may be used to project pressure variations. The method of trajectories used in this procedure is an application of the calculus.

The other method, used in this paper, is iteration, or trial and error. Different values of pressure are assumed and substituted in the water-drive equation until a value is obtained that will equalize both sides of the balance equation. In use, two or three pressures may be assumed, and the correct one determined by interpolation.

To illustrate the application of the prediction method, pressure predictions were made from July 31, 1939, based on the history up to that time.

At this date the cumulative water encroachment calculated by the material balance (case 1) was 2.47 million bbl., while $f(P, \theta)$ was 10,420. This fixes the value of C as 237.4. Pressure decline using actual production figures was calculated by the method described above. The calculated pressures given in Table 2 and Fig. 5 agree satisfac-

TABLE 3
Calculated future pressure behavior
Results plotted in Fig. 5

Date: End of period	Shut in	Calculated pressures: 12,000 bbl. per day oil, 150 net gas-oil ratio	15,000 bbl. per day oil, 150 net gas-oil ratio	20,000 bbl. per day oil, 150 net gas-oil ratio
1942				
April		1493	1493	
July	1492	1492	1486	1492
November	1527	1496	1484	1478
1943				
March	1560	1497	1481	1463
July	1594	1501	1477	1450
November	1626	1504	1471	1435
1944				
March	1653	1501	1473	1418
July	1680	1498	1465	1403

torily with those measured in the field.

Using the same method, pressure behavior for different production procedures was calculated for the next two years. Rates of 12,000 bbl., 15,000 bbl., and 20,000 bbl. of oil per day with a net gas-oil ratio of 150 cu. ft. per bbl. were chosen. It is evident from the pressure trends shown in Fig. 6, and listed in Table 3, that the gas injection is effective in maintaining reservoir pressure.

As a matter of additional interest, calculations were made of the pressure build-up to be expected if the field were shut in. The pressure increase would be slow, rising 187 lb. per sq. in. in two years.

Applications and Limitations

Material-balance calculations are useful in defining reservoir performance when only a small amount of the reserve has been produced. The magnitude of the pressure decline and the number and accuracy of pressure surveys are the controlling factors in applying these methods in the early life of production. They have been applied successfully to fields where only 1 or 2 percent of the oil in place has been produced. In these cases, precise pressure measurements, porosity and connate water, were available. One important point in the early history of a field is proper averaging of pressures during the development period.

In general, application of material-balance calculations are limited chiefly by lack of field data. The greater the number of dependable pressure surveys, the greater the accuracy of results. In the accumulation of field data, it is essential to keep accurate records of gas and water production as well as oil production.

Pressure predictions are limited by the amount and accuracy of pressure-production records when calculations are begun. Pressure data should be obtained only after carefully selected key wells have been shut in for a sufficient period of time for equilibrium to be established. An index of the shut-in time can be observed from build-up or productivity index tests. All wells in the field should be shut in during static bottom-hole pressure surveys unless the test wells are not affected by producing adjacent wells. In many cases, the estimation of future gas-oil ratios may be critical. More research on fluid flow will increase the accuracy of these prediction analyses.

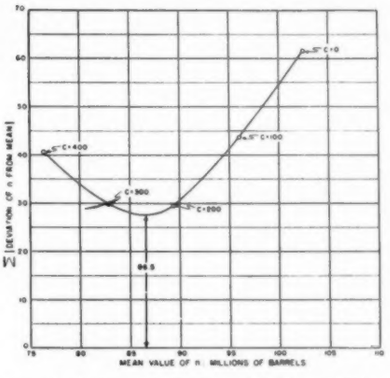
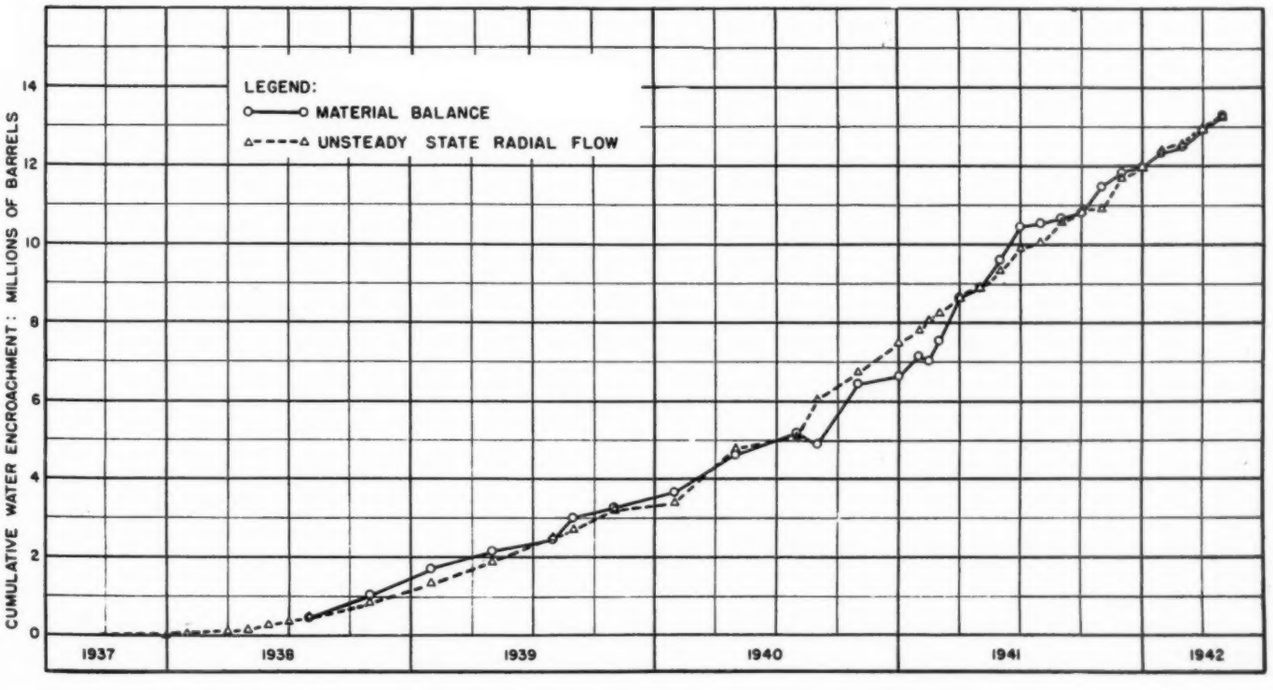


Fig. 4. Determining n and C by plotting deviation of n from its mean as a function of n and C

Conclusions

Quantitative methods have been presented that are applicable for identification and determination of magnitude of water encroachment, determination of initial oil in place, and calculation of pressure behavior in oil reservoirs. The methods are illustrated in a study of the Schuler field, Jones sand. Water encroachment was determined in two different manners (cases 1 and 2), and the initial oil content verified (case 2). With two years of pressure-production records as a background, pressure behavior for the following three years was calculated and compared with actual measurements. The satisfactory agreement obtained between the calculated and measured values authenticates the method used.

Fig. 3. Comparison of cumulative water encroachment obtained from material balance and unsteady-state radial flow



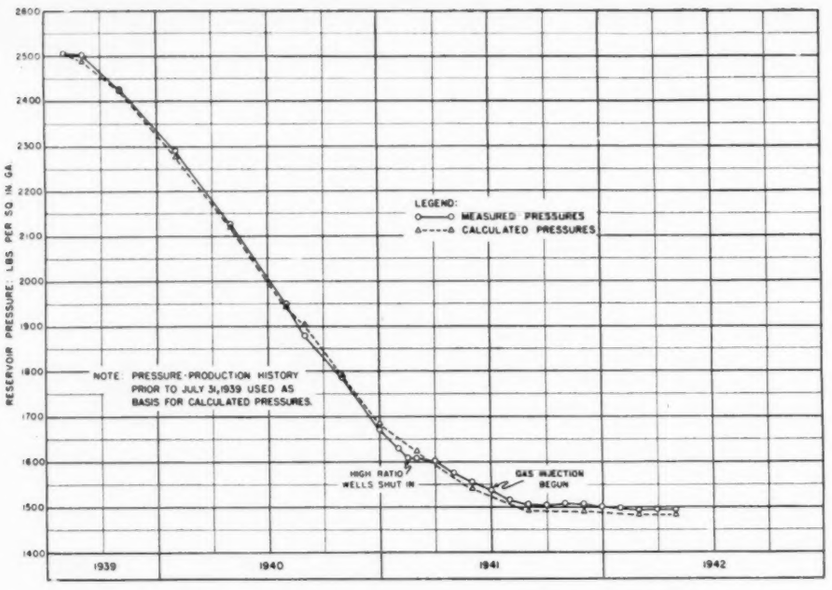


Fig. 5. Illustrating agreement between measured pressures and those determined from calculation of material-balance equation

Nomenclature

- n, stock-tank oil originally in place, bbl.
- Δn, stock-tank oil produced, bbl.
- u, volume of oil and originally dissolved gas in reservoir per volume of stock-tank oil.
- u_o, original value of u equal to 1.450 for Jones sand oil.
- r_n, cumulative net produced gas-oil ratio, cu. ft. per bbl., at 60°F. and 14.7 lb. per sq. in. abs.
- r_p, cumulative produced gas-oil ratio, cu. ft. per bbl., at 60°F. and 14.7 lb per sq in. abs.
- r_o, originally dissolved gas-oil ratio, cu. ft. per bbl., equal to 760 for Jones sand oil.
- v, barrels of gas in reservoir per cubic foot at standard conditions.
- v_o, original value of v equal to 0.000840 for Jones sand.
- z, barrels of water produced.
- Z, total barrels of water encroachment.
- m, original volume ratio of gas zone to oil zone.
- G, total gas injected, cu. ft. at standard conditions of 60°F. and 14.7 lb. per sq. in. abs.
- Z_i, total water injected, bbl.
- P_R, original reservoir pressure, lb. per sq. in. gauge.
- P, reservoir pressure, lb. per sq. in. gauge.
- K, permeability, cu. ft. per day per sq ft. per lb. per sq. ft. per ft.
- c, compressibility, cu. ft. per lb. per sq. ft.
- ϕ, porosity, fraction.
- α^2, diffusivity, sq. ft. per day equal to $\frac{K}{\mu\phi C}$.
- R, radius of reservoir, ft.
- H, sand thickness, ft.
- θ, time, days.
- σ, fraction of perimeter of field exposed to water encroachment.
- μ, viscosity of water in formation, centipoise.

It is apparent from this and similar studies that the use of the material-balance and water-drive equations when properly applied to field data gives a fundamental tool for evaluation of reservoir performance. One especially important usage is in the determination of pressure behavior. Critical rates of production may be established for water-drive fields. Rates and quantities of injected water to supplement natural encroachment may be predetermined. The effect of gas injection can be known before such program is initiated. Thus the effects of various production programs can be safely evaluated beforehand. When these determinations are combined with core-analysis saturation data, the economics of recovery under each can be analyzed, and the most profitable one selected.

These calculations can be made when reservoir-pressure measurements, production records of oil, water and gas, and bottom-hole sample analyses are known. Determination of structural dimensions using porosity, connate water and permeable thickness from core analyses will aid in earlier application and increased accuracy of results.

The importance of complete and accurate pressure and production records cannot be overemphasized. Reservoir pressure is affected as much by withdrawal of equal reservoir volumes of water and gas as by oil. The extra effort to measure and record these quantities is well justified in view of the increased knowledge of reservoir performance that may be gained by their use.

Acknowledgments

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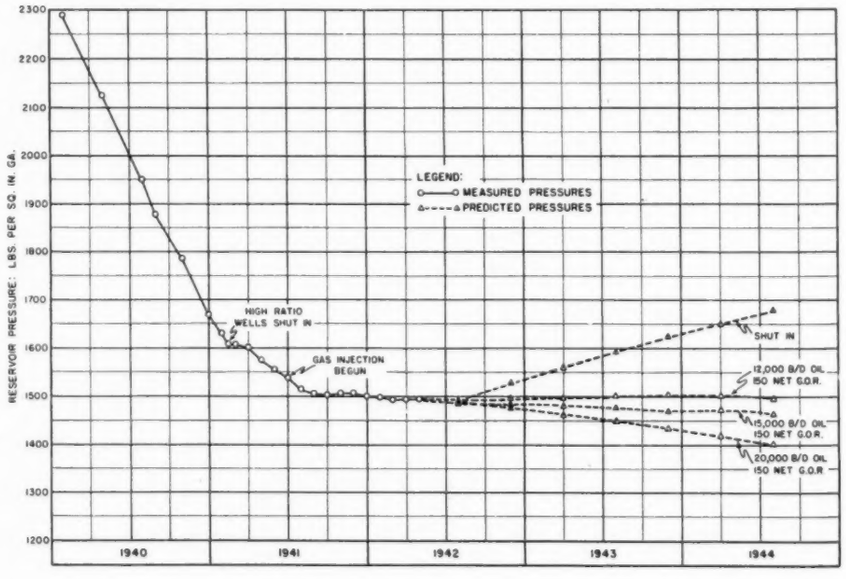

Fig. 6. Pressure predictions for different assumed rates in Schuler field, employing material-balance equation

Economics of Water Flooding*

By DONALD P. OAK
Lynde, Walter and Darby

I RATHER hesitate to present this paper as I certainly am no economist, as the term is generally used at the present time. As an engineer and operator, however, I am constantly faced with the question of whether an operation will pay out and return a profit, and it is from this angle of practical economics that I will approach the subject. I am sure that every petroleum engineer will agree:

1. That no oil reservoir is ever completely depleted by natural recovery methods.

2. That part of this residual oil can be recovered by some method of secondary recovery. The question of whether such an operation will be profitable or not, however, is another matter and at this point practical economics enters the picture, and should be the controlling factor from that point on in every commercial operation.

The subject is not simple and there is no magic formula that will give the answer. Conditions are not static, with practically every component a variable. On the engineering side secondary recovery is still in its infancy and technique is constantly changing, so that final results will usually be considerably different from preliminary estimates, due to increased engineering knowledge while the project is being developed. On the financial side, costs are changing rapidly, chiefly due to the chaotic industrial situation. Receipts should also be changing, but from the present attitude of the authorities, I might be inclined to class the sales price of crude oil as a constant.

Other conditions, such as the tax situation which has no direct connection with an operation itself, may change a development that would be decidedly unsound for one operator, to an advantageous one for another.

With these general conditions in mind I will approach the water-flood method of secondary recovery. There are four major considerations that an operator must take into accounting in a proposed water flood. They are:

1. An oil reservoir suitable to water flooding.
2. Source and supply of water.
3. Source and supply of power.
4. Marketing facilities.

Engineering and economics are so closely related in studying these factors that it is difficult not to digress into an engineering discussion. Preliminary estimates on water flooding are at best very uncertain, due to:

1. The impossibility of obtaining sufficient data on which to base an estimate without an investigation, which would virtually mean a development.

2. The changing technique in the operation of a water flood. Water flooding in the Mid-Continent area is only ten years old and we are only beginning to get complete histories and in the meantime technique has so changed that the history of the early floods are of little value in estimating future recovery. Taking up these four factors individually, here are some thoughts for the operator in making his decision.

1. Oil recovery. No preliminary estimate of recovery can be accurate, even with sand analyses from core wells on every 10 or 15 acres. Experience has shown oil content and sand conditions vary greatly from location to location. Of course, the greater the density of core wells the more accurate the estimate but also the greater the investigation cost.

Another thing to keep in mind is that even with the best present technique after a property is flooded out there remains more oil in the sand than the flood has recovered. What will the engineer be able to do about this in the future?

2. Water source and supply. Water source will, in the main, be either from river or deep wells, and the cost of either will vary with location. Great errors have been made in estimating quantity available. There is usually insufficient data on which to base an accurate estimate of a long-continued supply from deep wells, and the drought periods of the Southwest often interrupt river flow. Water supply failure in an active flood may cause serious loss of ultimate recovery and the cost of obtaining an emergency supplemental supply is usually very high.

3. Power source and supply. As water flooding is mainly the re-energizing of the oil sand, power is a very important factor, and it will probably take from 6 to 10 hp-hr. per bbl. of oil recovered. The source of this power will be either gas engines, oil engines, or electricity, depending upon which is available and cheapest. In most floods free casinghead gas is out of the picture. Although there may seem to be an adequate supply before the flood is started, experience has shown that it soon disappears.

4. Marketing facilities. Many floods are started in oil producing areas where the pipe line companies have restricted their capacity and are unable to take care of a large increase in production, forcing the operator to such other outlets at large expense to himself. An operator should assure himself of an adequate outlet.

Costs and Returns

All of this discussion has been leading up to the central theme of costs and returns. Costs will be divided into five principal items.

Leasehold cost. When a water-flood site is purchased the leasehold cost is definite and easily figured, but many operators already own stripper leases that have long since paid out and whose leasehold cost, when used as a flood site, is zero. There has also been a considerable number of flood sites obtained on an over-riding royalty, but it is my opinion that this practice will decrease in the future as the costs are too high. For instance, if the over-ride is one-sixth and a recovery of 3600 barrels is obtained the operator has paid in the neighborhood of $900 per acre for his leasehold. Not only has he given up the 600 bbl. royalty, but he has also paid the operating expense on it, which will amount to at least another $200.

Oil well development. So far the greater percentage of water floods have been located in the old shallow pools where most of the existing oil wells were in poor condition, and surface equipment was nearly worn out. The wells were also usually badly spaced to utilize as recovery wells. As it was nearly as cheap to drill a new well as to re-condition an old one, most of the old wells have been plugged and abandoned and the properties re-drilled with new wells and new surface equipment installed. Engineers have differed on well spacing, but the most common development has been 330 ft. by 330 ft. which produced a density of one well to two and a half acres; others have increased this spacing up to 440 ft. by 440 ft. or one well to four and four-ninths acres. I know only one instance where there has been a uniform spacing larger than this. The 440-ft. spacing decreases the number of wells by 25 percent over the 330-ft. spacing, with a corresponding decrease in development cost, although this is not 25 percent. However, there is an engineering question as to the point where decreased ultimate recovery more than offsets saving in development cost. There are two general types of production methods, pumping and flowing, and there is considerable dis-

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agreement among engineers as to the efficiency of each. Flowing has the advantage of lower investment and operating costs, while pumping gives quicker return on investment, but the big argument is difference in ultimate recovery. It is my opinion that this difference will be largely a matter of percentage, so that on high recovery floods the difference in barrels will justify the additional investment cost for pumping, while in low recovery floods, the decrease in development cost will be greater than the loss in production. Another item largely affecting the cost of development is the quality of equipment and pipe used. We are just abandoning a flood which was started in 1934, showing a life of nine years, and if developed at present time, I am certain its life would have been two or three years more. This may not be average, but I would not want to install pipe and machinery having an anticipated life of less than twelve years. It is better to install first quality equipment at the start, than to replace it half way through the life of the flood, with 80 percent of the oil recovered.

Also, most of the operators do not develop all of their flood at one time, so that they are still developing new territory when much of their equipment and pipe on the first unit is available for use in the new development. In this case, it is imperative to install the best material available, as it will be totally worn out before the entire project is exhausted. It is also important to design and install types that are best suited to transfer. In this connection I think the electrically operated pumping unit has a very distinct advantage over the central power. After three or four years pumping, when the water-oil ratio and pumping costs per barrel are high, the well can be put to flowing and unit pumper moved to a new well, while the central power must remain in operation as long as it is desirable to pump a single well. The original cost of surface equipment for a central power operating wells on forty acres, compared with individual pumping units with transmission lines, is practically the same. In 500-ft. territory this amounted to about $360 per well two years ago, but with present increased costs, it would be nearer $400. It has also been found that the water produced with the oil is extremely corrosive, so that in first installation all oil lines should be protected, as they will have to be replaced in a few years if not. Transite pipe or cement-lined pipe is the most common method. Secondhand line, even of poor quality, is very satisfactory if cement-lined.

Depth of the oil sand directly affects total development cost. Surface lines and tankage, of course, will be the same but drilling, casing and to some extent, pumping unit costs, increase in proportion to the depth. Drilling costs will vary with different fields, but rarely exceed $1.00 per ft. in present developments.

Another development cost sometimes omitted in estimates is the salt water disposal system. All water floods will soon produce considerable quantities of water of varying salt content. In order to avoid pollution problems it is best to design a system to return the water to water plant, for treatment and recycling.

In addition to regular costs, many operators have added another initial cost in the coring and analysis of the sand on every well drilled. This work has resulted in the use of heavier shots, so that total increased cost may reach $250 per acre, but they anticipate that increased returns will more than justify increased costs.

Before discussing total development costs, I will proceed with water system development, as most operators group the two developments together in considering total costs.

Water system costs. The greater percentage of water floods use the five-spot system, where in general there is the same number of water injection wells as oil wells. Edge development will vary this proportion slightly. All water injected into the sand must be in condition so as not to plug the sand pores, and if unprotected pipe is used, it must be non-corrosive. In all open type systems where the water comes in contact with the air, it must be treated and filtered. Advocates of the closed type system claim they eliminate these costs, but as they still have the salt water disposal problem on their hands, and treating costs are low, they have not as yet convinced me as to the advantage of their system. Pressures to be used are dependent on depth of sand, well density and sand permeability, and whether oil is pumped or flowed. The greater pressure used the higher the installation cost.

Again, the cost of raw water supply varies greatly. If a river supply, the cost of intake installation and pump at river and length of pipe line to plant govern, while in the deep well supply it is the cost of drilling and equipping supply wells. In Eastern Kansas most supply wells will not furnish in excess of 1500 bbl. per day each, while in Northeastern Oklahoma their capacity is much greater. Also, in case of supply wells, some provision must be made for surplus supply while wells are being re-conditioned, which is necessary periodically because of the corrosive salt water produced. Cost per acre for a water pressure and treating plant is much less on a large project drilled by units than on a property entirely developed at one time. In the latter case, capacity must be figured for maximum demand for entire property, with resulting idle capacity in latter stages of flood, while in the former, as demand decreases for first units, it is absorbed in development of additional units, with the pressure plant operating at capacity over a long period of time. In large projects the question of whether to use one large central plant, with large long high pressure main water lines, with attending high friction loss of head, or to use several smaller plants with short small main lines and low friction loss is one which requires careful study. Drilling costs are nearly identical with those of oil wells but equipment is much less on a pumping project.

Over-all development costs. While oil well and water system constitute the major part of development costs, there is a third which is considerable, although often overlooked. This is the general investment, not applicable to any one lease or department, and includes truck equipment, surface inventory, heavy tools, repair shops, housing facilities, etc. In most instances it will equal 10 to 20 percent of other development costs.

I have tried to point out that each project requires individual study to make an intelligent estimate of development costs, but to illustrate the ranges in which they run, the lowest total development of which I know, for a completely re-drilled flood in 500-ft. territory, in which the new wells were equipped for pumping, was about $1250 per acre, and will range from that figure to $2500 per acre in 800-ft. territory. Floods equipped for flowing will have considerably less investment, of which the lowest in my knowledge is $800 per acre. On a cost per barrel of oil recovered, these costs will range from 30 to 65 cents per bbl.

Expense items may be divided into three classes, namely:

1. Production expense. The production expense per barrel of oil produced will naturally vary greatly in the life of a flood, from a low cost during peak production and advancing with declining production until economic limit is reached and flood is abandoned. The most important factors are labor, power, repair, oil treatment, and taxes. In a pumping flood, labor and power are much larger than in a flowing flood. Except for a short period, when the first unit is at its peak production, production rarely exceeds 10 bbl. of oil per well per day, so there is usually a large number of wells to service with corresponding expenditure of manpower. Troublesome wells, with high pulling expense, can be controlled somewhat by converting to flowing

wells when expense per barrel is too high. Experience has shown that water produced with the oil is highly corrosive and in early projects maintenance and repair of oil lines has been a large item, but in new installations it is now important to use cement-lined pipe or Transite, which reduced this expense to a minimum. In pumping projects the water produced with the oil separates into small particles, and it is necessary to use considerable treating compound, and in the lower gravities in Eastern Kansas it is necessary to install an oil heating system, which adds very materially to the expense. While there is very little true emulsion, the water particles are extremely slow in settling without treating and heating. Taxes are fixed and the assessment valuation should be watched carefully.

2. **Water system expense.** This expense may be divided into power, treating, operation, labor and maintenance, and repair, of which the first three are the most important. Raw water from surface supply or deep wells must be lifted to the plant site; this head with surface supply is rarely in excess of 50 ft., while in deep wells it may reach 500 ft., and this power cost may well be one of the determining factors in choice of water source. Power cost in the pressure plant is in direct proportion to pressures and quantities used, so this factor should be studied in choosing method of development. All plants should be designed to need as little operating labor as possible. If good equipment is installed and maintained, and care i- taken in the water treatment, maintenance and repair of the water system is light, but if water treatment is neglected all kinds of trouble will develop in the water system, causing heavy expense. If a plant is well designed the treating cost is not heavy, usually running from one to three mills per barrel of water with surface supply. On this account I do not advocate closed systems which eliminate this cost, but do entail other increased costs, such as additional power and higher maintenance which may more than offset treating expense.

3. **Overhead and administrative expenses.** These will vary with each operator. Many of the larger operators still include their secondary recovery projects in their regular production department and charge it on a barrel basis with the same proportion of the discovery, exploration, and general overhead costs. I do not believe this is good practice, as secondary recovery is a distinctly new branch of the industry, and as such should have a department of its own, with the administrative costs of that department only charged to it. Some smaller operators pay large executive salaries as a part solution of the income tax problem, which also complicates the situation.

Grouping all of these expenses and starting with a minimum of 2000 bbl. per acre — as any intensively developed pumping project having less recovery than that cannot be a financial success at the present time — experience has shown that over the life of a project production expense will vary from 15 to 30 cents, water expense from 10 to 20 cents and true administrative expense from 5 to 10 cents per bbl. of oil produced. Totaling these items gives a minimum of 30 cents and a maximum of 60 cents per bbl. of oil, with the lower recovery projects usually going into the high expense brackets.

Total flood operations will have little influence on crude prices, so that it is a foreign factor on which each operator will have to make his own estimates.

Total costs, including both investment and expense, will range from 60 cents in favorable locations to as high as $1.20 per gross bbl. oil produced in intensive developments under present conditions. These figures, however, are very general and each individual project has to be worked out on its own merits. Water flooding approaches a manufacturing operation and as such the most efficient methods must be used to reduce total overall costs to a point where a profit can be anticipated. —— ☆ ☆ ☆ ——

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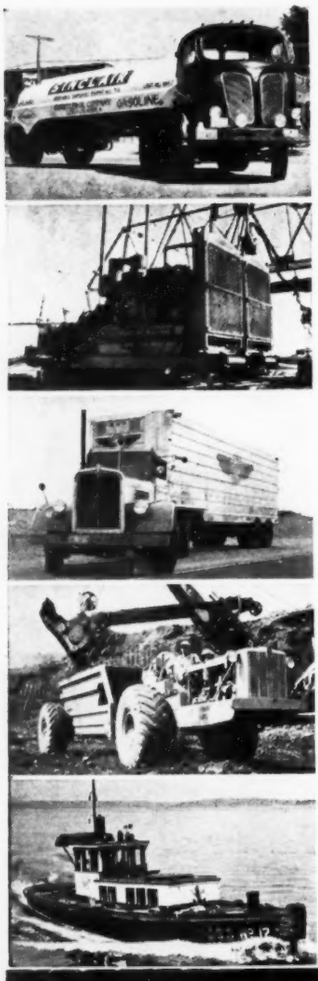

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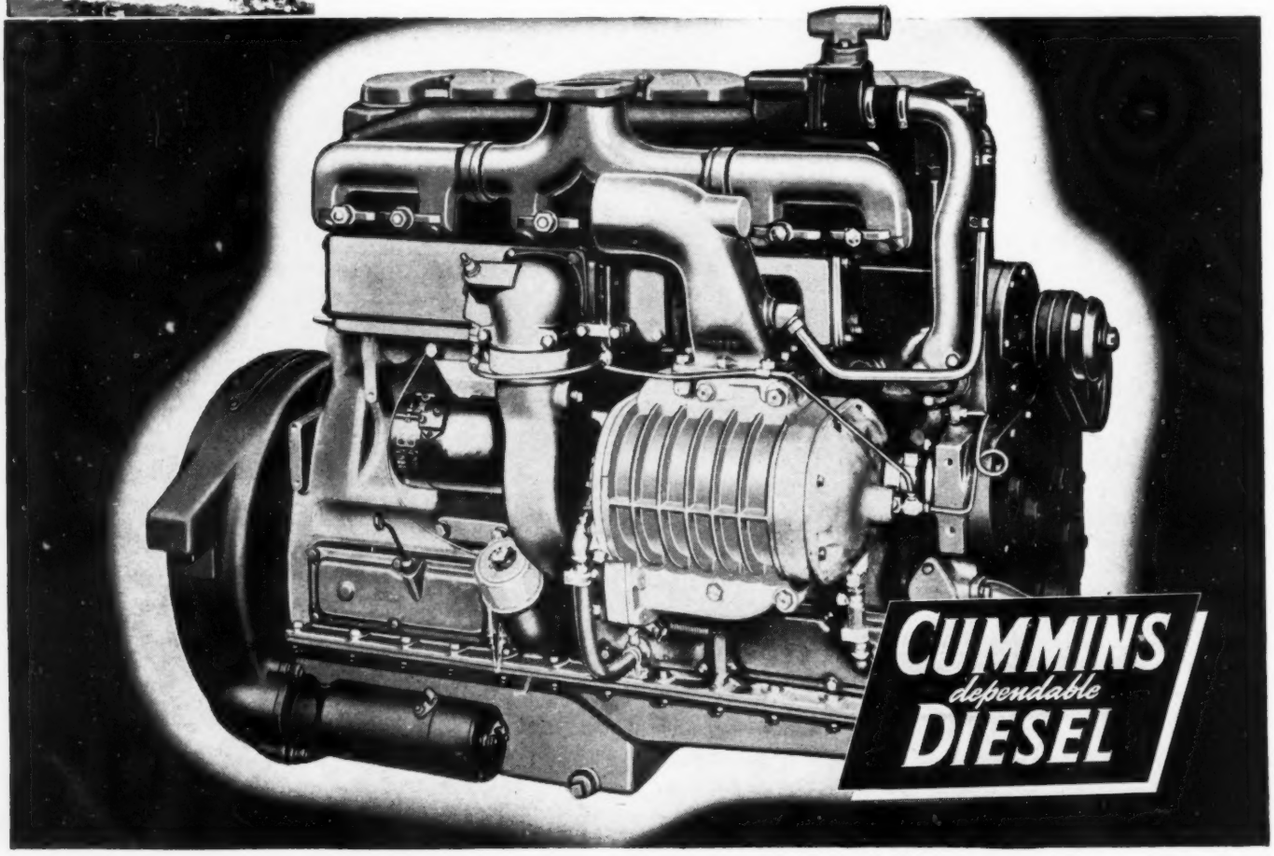

Flowing vs. Pumping Operations in Water Flooding*

By

T. F. LAWRY

Engineer, Forest Producing Company

FLOWING in water flood operations has been looked upon by most operators of that type production from all viewpoints in the Mid-Continent and the Pennsylvania fields, but for most of them final results have not been encouraging. As a representative of perhaps the major water-flood operator in the Mid-Continent area, I have been asked to participate in this afternoon's program to the extent of outlining some of the procedure used by our company in flowing its production, as well as to attempt to explain to my listeners why we are so sold on flowing that not one barrel of oil is pumped if the same can be flowed. I shall attempt to explain why we feel that flowing is a very desirable means of production, admit some of the shortcomings of flowing, and attempt to show why we think that we get as much oil by flowing as we would by pumping.

All reference to the word flowing in this paper will mean that act of oil production whereby the oil and water produced from the oil well are brought to the surface by the carry-through of pressure in the sand of the injection water. Fluid is permitted to accumulate in the oil well and in the sand until the pressure of the injection water traveling through the sand is sufficient to lift the fluid in the bore of the oil well. Of course, any water-flood under pressure above hydrostatic will flow if the oil wells are permitted to stand unpumped until full, but in most cases that is considered a nuisance rather than an easy way to get the oil out of the ground. If an operator goes to the bother of putting tubing and rods in a well, he does not want it to remain unpumped long enough for the hole to fill up. He wants the sand to remain uncovered, or nearly so, to get the benefit of that last ounce of pressure from the water wells, and not waste any of that pressure lifting oil in the hole.

Flowing is not an innovation in the Mid-Continent area. Many of the early floods in the Bradford, Pennsylvania, field were experimented with in various attempts to get them to flow and save part of the huge lifting cost that the Pennsylvania area has always contended with. But for reasons invisible and obscure, no great to-do was made over the result with the flowing experiments there, and for the most part, flowing was considered a failure.

As far as the writer knows, the first serious attempt at flowing was Forest Producing Corporation's Flood No. 1. This project showed perhaps the first inkling that flowing was a distinct possibility when the producing wells came in flowing great volumes of oil. This flood had been drilled in accordance with the delayed five-spot plan in which the water-intake wells are drilled six to nine months ahead of the oil. During that time, the water being injected fills the void areas in the sand, recompressing the free gas, and driving some of it back into solution, until finally 100 percent liquid saturation has been attained. This point shows very well on the intake records, for it appears as though the water had run into a stone wall.

This point of liquid saturation is the high sign for the operator to start drilling his oil wells. The first ones will come in violently and usually shower oil all over the countryside unless advance precautions are taken to keep the well under control while the sand is being drilled and the packer set. If the water-intake wells are left on during the time the packer is being placed, and while the cement on the packer is hardening, the well will continue to flow. It is, of course, this steady flow of good oil that makes it hurt so to think of running an expensive string of rods down the hole to lift the oil that is already being lifted.

This matter of delayed drilling is the first of two departures from conventional operations in flowing. A logical question here would be why not drill the oil and water wells together, and shut the oil well in until that point of 100 percent liquid saturation had been reached, and then open the oil well and begin taking the oil without all the fuss and mess of drilling the oil well into the formation when it is under pressure. This is perhaps an unnecessary digression from the subject of flowing, but it is a question which we asked ourselves at one time, and had to find the answer the hard way. There is an honest difference of opinion among operators on this point, so perhaps our experience will help someone else avoid the same mistakes.

In the Bartlesville sand area, we find many variations in sand conditions from well to well and pool to pool, with the consequence that no two wells may ever be said to be alike. Some operators have attempted to overcome the shortcomings of sand conditions by coring all wells and selectively shooting the sand in an attempt to even out the variations. This is a fine approach to the problem, but hardly one for a company with 10 strings of tools running all the time and only one man in the laboratory. So we accept the non-uniform sand conditions and try to live so they will give us the least amount of trouble.

If we take one well as an example, we may find that it has a fairly uniform permeability profile except for one five-foot streak in the middle which is about three times as permeable as the average. If that well is shot without regard for the more permeable streak, and is equipped for water injection and put to work, the first thing that will happen is that the streak will start to take more water per foot of sand than the rest of the section, and in a short time, the oil in that streak will have been pushed on through the five-spot and will begin pouring into the shot-hole of the already-drilled oil well. If the oil well has been shut in, the air or gas in the tubing of the oil well will be compressed, and the fluid will partially fill the tubing, then if there is still oil to come from the streak, pressure will begin to build up on the oil well and a back-flood of oil will begin to work on the less permeable section of the sand in the oil well, because the less permeable section of sand in the water-intake well has not received enough water to pressure it through the five-spot from the water well to the oil well. So we find water in the water intake well working on the tight or average permeability sand while across the five-spot in the oil well we have a back-flood against that same sand but the back-flood is by oil and rightfully we are getting no place in a hurry. For a long time we thought that we were not losing anything because we would get that back-flood oil out again, until we ran some laboratory experiments and found that we do not get that oil out at all; in fact the sum total of it is that we lose oil because where in normal operations we can reduce residual oil saturation to about 20 percent in the cores flooded with oil, the best that we were able to reduce to were oil saturations from 30 to 40 percent; in most cases

*Presented before Mid-Continent District American Petroleum Institute Division of Production, Tulsa, Oklahoma, May 20 and 21, 1943.

we left more oil than what we started with.

What apparently happens with back-flood by oil is that the oil drives out the connate water to an extent that the sand becomes hydrophobic or oil-wet instead of water-wet, and in that situation will normally have a much higher residual saturation.

If the loose streak should happen to hold only a little oil, not enough to fill the shot-hole and tubing of the oil well, we have a back-flood by water into the average-permeability sand, and again work against ourselves, in effect delaying the bringing-to-production of the flood by as much water as is permitted to back-flood through the oil well. So for the reason that a back-flood by oil or water is a delay, and for the further reason that a back-flood by oil actually loses oil as well as delays, we consider the drilling of oil and water wells simultaneously poor practice, and refrain from it unless forced to it by unfortuitous circumstances.

Having considered the case for delayed-drilling as the first departure from conventional operation in connection with flowing, the second departure is that of cementing the tubing on a packer in the oil wells. Almost all water-intake wells are cemented in with packers as a matter of good operation without a second thought, but the finality of cementing the tubing in an oil well is too much for a lot of operators. They like to feel free to yank the tubing out if the well doesn't act right, and go in with a sand pump or second light shot, and see if they can't "get her to working right". Of course, they have to yank rods and tubing often enough when they are pumping an oil well, so it becomes second nature to do the same if anything else goes wrong. In flowing, this cannot be done, but several next best things can, and in flowing at least there are no valves or cups to change.

The advantages of flowing over pumping are many, and the corresponding savings quite appreciable. Because they are so closely united, they will be treated together.

Perhaps the first advantage that might be pointed out would be simplicity of operation. Except for a few of the very deep water-flood projects which operate by gravity, it is safe to say that all water floods have a pressure plant to force the flooding water into the sand. If that same plant can be made to serve the dual purpose of putting water into the ground, and taking the oil out, the mechanical problems have been reduced to their simplest form. And that is just what flowing involves. Instead of the pressure head being entirely expanded in the formation as is the case in pumping, part of it is reserved to lift the oil and water from the bottom of the oil well to the surface, eliminating installation of central powers and pumping jacks or individual pumping units to do the job. All the arguments over flowing revolve around this point; whether it is cheaper to risk not getting as much oil by flowing, or do the job the expensive way and pump to get what is hoped is more oil than would be obtained by flowing. Later I hope to show at another point why I feel that flowing is cheaper and yet will yield more oil.

By utilizing the energy from the pressure plant and omitting the central power or individual units, there is of course less machinery, and fewer moving parts to maintain, lubricate, and replace periodically. The prime-mover begins to wear out and becomes harder to keep going; the belt stretches, and finally wears out, and the eccentrics on the power wear thin in one place and finally break down; the surface rods get thin from running over the same post day after day; the pumping jack foundation pulls loose, and gees around; the sucker rods become fatigued and break with greater regularity, and the load on the oil wells becomes greater with more and more water to be handled as the age of the flood advances, and valves and seats wear out faster and faster. To the harassed operator of a pumping water flood this matter of simplicity of operation is a serious thing.

In addition to mechanical simplicity, we find the man-power situation also simplified. The water-plant man or water-meter man, depending on whether the project is small or large, can take care of the water-pressure lines and wells and keep things going on that end regardless of how the production is obtained. If the lease is pumped, the pumper usually looks after the oil wells and lines, but in addition, he must see that the pumping engine is kept running and well lubricated; keep his rod lines greased so the wells will get all of the stoke possible on the power, and at the same time depend upon the well-pulling crew to keep his wells in shape so he can keep his production up. So it is quite easy to see that the the comparison between the switcher on a flowing job, who has nothing to do but check his oil wells and oil lines and occasionally change from one tank to another, and the pumper who must baby his engine along nine months of the year because the gas is low, and hound the foreman to get such and such a well pulled today, because it is the best one on the lease, as well as act as oiler to a thousand places that squeak at will; it is safe to say that the switcher does a lot more toward escorting the oil to the tanks than does the pumper.

Material Saving

The material that is saved by flowing against pumping has been implied in the above. All the pumping equipment except a string of tubing can be saved, including usually a string of casing. If the hole is wet during drilling, a temporary string is usually run until the cement on the packer has set, then the casing may be pulled for reuse.

In the past, the amount of material tied up did not matter so much because it was considered a necessary evil to install a good substantial power unit and run the surface rods right the first time, for goodness knows they would get out of line and order soon enough. But the material could be used from well to well or flood to flood with replacement of worn parts and the feeling that the old power or jack had already paid for itself, so if it only ran for a year and then needed replacement, that year would still be gravy. But now the horror of it is that so much iron and steel must be tied up to do the job in a hurry.

When Forest's Flood No. 1 was converted from pumping to flowing, we found another advantage in flowing that had not been readily discerned. On the two leases which were converted from pumping to flowing, there is a distinct upward displacement of the decline curve followed by a more gradual flattening of the curve than obtained during pumping. All leases were drilled according to the delayed-five-spot plan as mentioned earlier. One example illustrates what usually happens to an operator who had drilled oil and water simultaneously and began pumping his oil wells immediately. He had a very nice peak production, after which began the steady decline until the economic limit by pumping was reached. Accordingly, he shut the powers down, and waited to see what would happen. At the end of the first month something apparently disastrous had happened; production was down to half of what it was when the powers were stopped. Most operators throw up their hands there and call us nuts and go back to pumping. But this one had anticipated such a condition and decided to see what would happen the second month. Surprisingly enough, there was little or no variation that month, nor has there been much, if any, in almost a year. For any one of the many reasons which might prompt him to do so, this operator began taking oil as soon as it came into the oil wells and did not wait for 100 percent fluid saturation.

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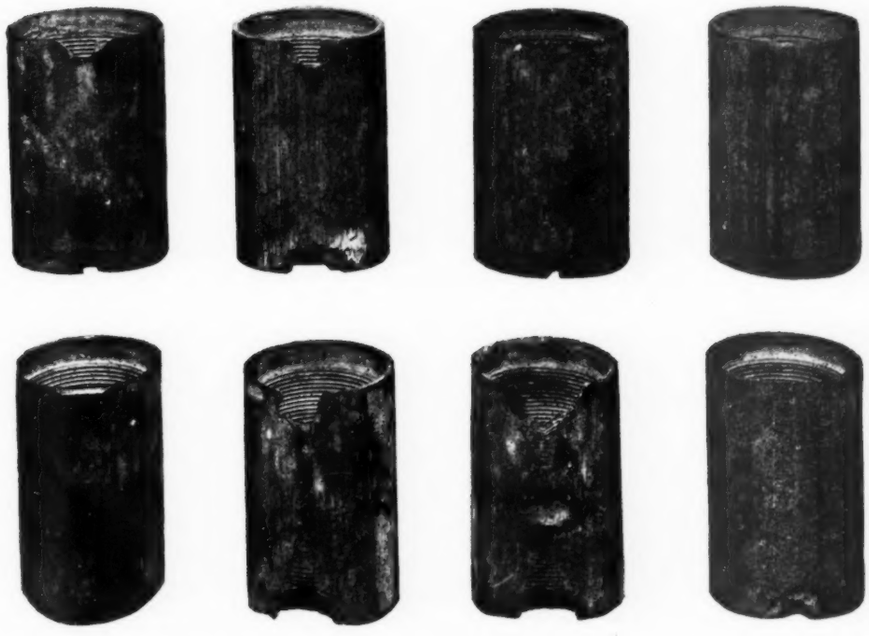

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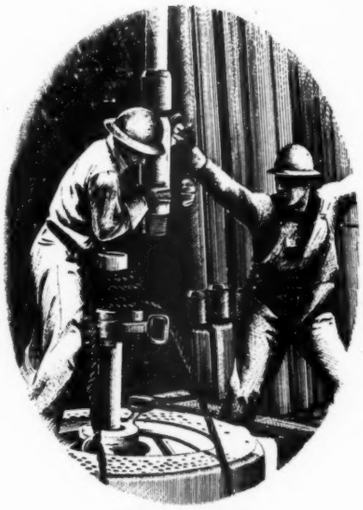

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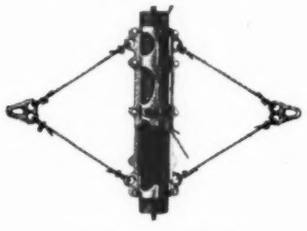

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Now that there is back pressure on the oil wells, he is waiting for that 100 percent, only at the same time he is getting production from the flow lines or part of the five-spot already saturated. There is not the slightest doubt in my mind that he will get more oil for having converted to flowing than he would have been able to get by pumping, if for no other reason than the fact that he now will have at least saturated all of the producing acreage, and he had not done that under the original plan of development. This operator is not Forest, but the data was kindly released for me to use. One last thing that I might say in this connection is that the operator quite calmly saw that waiting for a second month was the thing to do, because the conversion from pumping to flowing only reduced the pressure drop through the sand by ⅓ of the total sand face pressure, so that the drop in production to ½ must be ascribed to something besides back pressure alone.

Limited Withdrawal

A new technique used in water flooding that is best adaptable to flowing projects is that of limited withdrawal, similar to that used in flush fields under proration where the days production is taken in a few hours or minutes and the well shut in again for the remainder of the 24-hour period. In waterflooding, the oil wells are drilled when 100 percent liquid saturation is attained, and as nearly simultaneously as possible, so that all wells are at peak production at one time. When all of the wells have been drilled, the packers on the bottom of the tubing cemented in, and the wells capable of being shut in under pressure, the oil wells are flowed wide open for a day or two to determine the potential of the lease, after which some pre-established time or fraction of the day from 18 to 22 hours is taken as the daily quota. That gauge is given to all switchers as the amount to take from that lease and no more. For a day or two it will take that long to get the oil, but shortly the time will have been reduced by one-half an hour, then an hour, and on down until possibly only 12 hours will be needed to get what used to require almost a full day. In the meantime, the oil wells are shut it, and allowed to pressure up with the intake wells going along unhampered 24 hours a day. Where a well produces only one-half of the day and is shut in the other half, a very healthy back pressure builds up, and the production when the well is finally turned on, scampers through the oil lines to the tanks with haste and dispatch. But if the budget should show signs of falling behind, and this lease shows signs of helping out, maybe by just sneaking on through the whole 24-hour period for a day or two instead of shutting off at 12 hours for a period of reinflation, the results are apt to be sorry. After the first day when most all of the back pressure will have been expended, the lease will have trouble making in 24 hours what it made with ease in 12 with back-pressure. Water starts to come through in increasing amounts, and the lease acts like any that has passed its peak and started down the long decline. Only by starting at a lower figure and gradually building back can the original figure be reached, and that only if the water break-through was not permitted to progress too long.

The ideas behind this plan might be described this way: when an oil well penetrates the formation under pressure, certain flow lines or patterns are established—in a homogeneous medium they might be considered a series of pipes running in the shortest possible line from intake to producer, and only as wide as the fluid moving at any one time would require. Now if we drill an oil well into the sand, and establish these patterns, and never do anything to throttle those same pipes, there is little reason to believe that any of the other little pipes in the five-spot will ever be called into operation once their original pressure has been expended. But by alternately pressuring and relieving the pressure on the formation, oil will be forced along into those most active pipes and become recoverable oil. It is assuming much to look at the actual operation as functioning in that manner, but we do feel that the alternate pressuring and releasing of pressure must cause that ordinarily unaffected oil to move along out into the zone of active influence.

Some of the things that we have seen in connection with this limited withdrawal technique are: (1). In no case have we failed to get more oil on the lease where this was used than from adjoining leases where the conventional 24-hour flow was used. (2). Flooding efficiency, or the percent of the total recoverable oil obtained by the time of appearance of the first water at the producer, is always higher. (3). The danger from water bypassing oil in the sand is substantially lowered due to the fact that a good bank of oil is kept ahead of the water, and because of the back-pressure somewhat lower injection rates are employed.

Among the objections to flowing, the primary one is that it keeps a back pressure on the sand and lessens the actual work done by the injection water. We admit that the back pressure is there, in fact we deliberately add to it to increase our recoverable oil. Our results seem to indicate that the highest possible pressure attainable is not necessarily the most economic because of the danger involved due to too high rates of injection causing bypassing of oil. Many of the watered-out areas in the old Bartlesville field show residual saturations lower than we can obtain by our forced water-drive, yet they operated at probably less than hydrostatic pressure. More often than not the conversion to flowing from pumping produces the effect discussed in our previous example, but the only reason the operator can see for his decline in production is back pressure so he has a bad taste in his mouth for flowing.

A second objection to flowing is the necessity for cementing the tubing in on the packer. This really is no trouble until a leak develops in the tubing. Then a companion string of pipe with left-hand threads is used to fish the offending joint out by unscrewing the original right-hand thread pipe as far down the hole as possible, and then substituting the left-hand thread pipe to get a new hold and unscrew further down the hole.

If it becomes desirable to clean suspected cavings from the whole, an insert string of pipe, ½- or ¾-in., may be run and the hole subject to alternate or successive flushings and purgings with water and compressed air.

Like all of the attributes of water flooding, flowing has certain expressed or implied shortcomings. It is not a cure-all, or a positive profit-getter. If the operator has not made the necessary preliminary investigations to determine sand conditions, but goes out and puts water down one well, and goes over to the other to await the voluminous flow of black gold, the chances are he is doomed to disappointment. He usually picks the poorest spot to start on because he has no assurance that it will work. Or if he goes by his old production records, and takes what was once the best spot, he may be right in the middle of an old natural or accidental water drive, and yet expect a second drive to work all over again. Most operators are smarter than this, but you hear of things being done like that every day. Water flooding or baking bread can be done well, or can be failed at completely, for no greater reason than leaving the salt out of bread dough, or failure to find out in advance whether there was any oil left in the sand to flood out.

☆ ☆ ☆

Remedial Work in Oil Fields of the Eastern Area of the United States*

By

W. N. LITTLE

Tide Water Associated Oil Company

Abstract

PATTERN water-flooding oil sands in New York and Pennsylvania, especially in the Bradford third sand is an effective way to procure maximum secondary recovery of oil. Large acreage in this Appalachian area is currently being converted to water-flood operation. Charles R. Fettke estimates 60 percent of Pennsylvania grade crude from this area is being produced by water-flooding. The Louden pool in Illinois is possibly the best example of pressure maintenance of oil sands by gas injection in the eastern area.† At least 100 wells in this field that pumped at first now flow their production. Many of the new fields of Illinois, Indiana, and Kentucky have numerous productive zones in each well. A common practice is to produce the deepest formation first and open shallower zones when production facilities allow. The multizones are produced together from the deepest horizon. Methods of opening additional oil zones into an old well are discussed in detail under the heading of new field work.

Introduction

In this paper "remedial work" is understood to cover those methods by which oil production is increased, either through opening into the well bore shallower or deeper formations, or by increasing the energy in the present producing horizon, and thus forcing more oil into the well bore.

Scarcity of strategic metal and rubber material increases the demand on the petroleum industry to improve present methods, and develop new methods to obtain greater recovery from known reserves. This discussion will include secondary-recovery efforts, using air, gas or water for energy, which has had wide use in the Appalachian area; pressure maintenance in some of the newer flush fields—for example, Louden in Illinois—which give indications of increasing primary recovery in some places 20 to 25 percent; and the practice of multizone completions. This last method is of great importance at this time because it makes possible the saving of thousands of tons of steel and permits recovery of some oil from horizons that could not be considered commercial, should it be necessary to drill wells to produce such horizons.

*Presented before American Institute of Mining and Metallurgical Engineers, New York, New York, February, 1943.

†J. R. Randolph, New Harmony Repressuring Association (formerly Carter Oil Company, Louden field), Crossville, Illinois.

Secondary Recovery

Secondary recovery predominates in the states of New York and Pennsylvania and is very important in West Virginia, Ohio, and Kentucky. Very little secondary recovery is carried on in Indiana or Michigan. In Michigan, eight air and gas repressuring projects have been attempted with little success. The discovery of new fields in Illinois, and to some extent in Indiana and Kentucky, has curtailed extensive secondary-recovery work. Some of the old fields in Illinois have reacted favorably to gas repressuring. Pressure-maintenance projects in some of the newer fields of Illinois possibly will stimulate secondary-recovery efforts in the future.

The status of secondary-recovery operations in the eastern area of the United States is shown in Table 1.

Water-flooding. It is estimated by informed engineers,[2] that 60 percent of Pennsylvania grade crude produced in the Appalachian area in 1940 was produced on water-flood properties, and that this rate of production can be continued for another decade. Only in the past year has pattern water-flooding been attempted in Illinois, and it is too early to forecast results.

The most generally accepted pattern is the so-called "five-spot," in which each producing well is surrounded by four intake wells. Ordinarily, in the Bradford-Allegany area, the distances between the producing well and the intake wells range from 200 to 240 ft. Shallow subsurface fresh water is injected under pressure, which, assisted by hydrostatic head, generally ranges from 1500 to 2000 lb. per sq. in. against the producing horizon. Although the general practice is to pump the production, in some places by application of high intake pressure, the production has been flowed.

The Bradford third sand, which covers a sizable area, has given the best average recovery to date of any sand flooded. This sand has an average permeability of 5 to 10 millidarcys and an average porosity of 15 percent. Experience here indicates that after the water injected reaches the oil producer, it is necessary to handle 7 bbl. of water per barrel of oil. Fig. 1 shows the effects of water-flooding on production in the Bradford field.

Mining or horizontal drilling. Mining of oil sand has not yet been at-

[2]References are at the end of the paper.

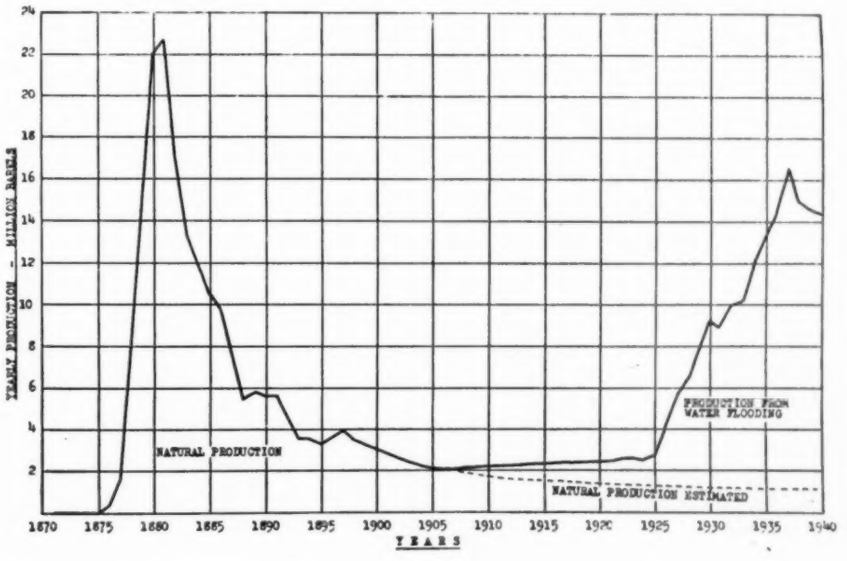


Fig. 1. Production curve of the Bradford field
(From C. R. Fettke[2])

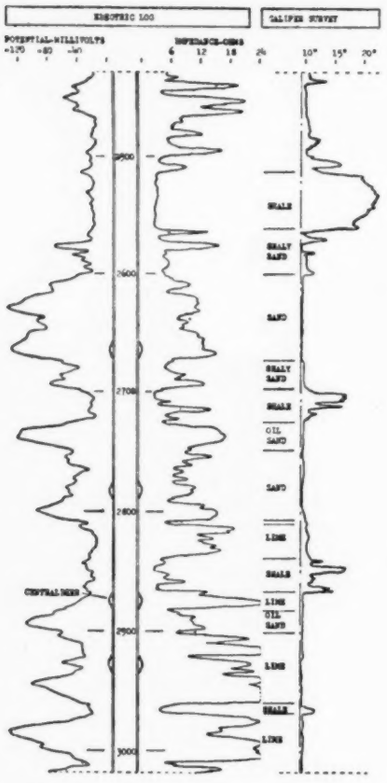


Fig. 2. Composite electric log and caliper survey of an Illinois well, showing spacing of casing centralizers

tempted in the eastern area, but of interest is a modification of mining now being attempted in Franklin County, Pennsylvania. In this operation a shaft has been sunk to the shallow producing horizon and from this shaft radial wells drilled horizontally through the sand are contemplated.[3] Proponents of this method estimate that only 0.28 lb. of steel per bbl. of oil recovered will be required, in comparison with present pattern-flood requirements of 4.19 lb. of steel per bbl. of oil.

Gas repressuring. In gas repressuring, gas is injected instead of water, the best results being obtained by using a pattern similar to that used in water-flooding. In the gas-repressuring area, such factors as low oil content, lens-type sand formation instead of a blanket sand, oil price, excessive development cost due to depth, or casing requirements generally make it economically unsound to apply efficient patterns. Therefore, the input wells generally are located in the most symmetrical position possible with regard to the producing wells. Best results are obtained if the injection wells are drilled and the sand cored, as by analysis of the core for permeability, porosity, oil and water content, the operator can at least apply pressure on the part of the sand that is most likely to respond to his efforts.

In Pennsylvania, because of multiple sands, new input wells usually are drilled, and by setting several packers gas can be injected at different rates and pressures, to serve properly sands of different characteristics.

In West Virginia and Kentucky, old wells in the center of a group of wells are generally used for injection purposes, with little regard to condition; that is, poor wells that indicate low permeability, thin or shaly sand, are frequently used.

In Illinois, operators in the old shallow area report best results with air and gas repressuring when new wells or the better producing wells are used as input wells.

Reconditioning Old Wells

Almost all the eastern oil-producing states have great numbers of old wells. Many of these wells have produced by primary recovery methods for 20 to 60 years. A good production increase for a rework job in the Appalachian area, or any of the other older areas, may bring a well's weekly production from 1 bbl. to 8 bbl. Such small-scale increases are profitable because of low operating costs and contribute to the amazingly long life of most wells. The market price of oil is also a major factor. Table 2 outlines some reconditioning methods used in Appalachian oil fields.

New Field Work

Cementing technique. Fourteen possible oil-producing horizons exist above the St. Louis limestone in some areas of Illinois. Six of these zones have proved productive in some of the fields, and deeper production possibilities exist in many of the pools. This condition exists in some degree in other states. Casing usually is set over the deepest pay sand, or, should the bottom pay be lime, the oil string often is set through the producing zone. Forethought of future method of opening upper zones is given at the time casing is run. Ample cement is used to protect all productive zones with a centralized wall of cement. Various makes of casing centralizers are frequently spaced above and below each productive horizon.

TABLE 1
Secondary recovery, Eastern area*

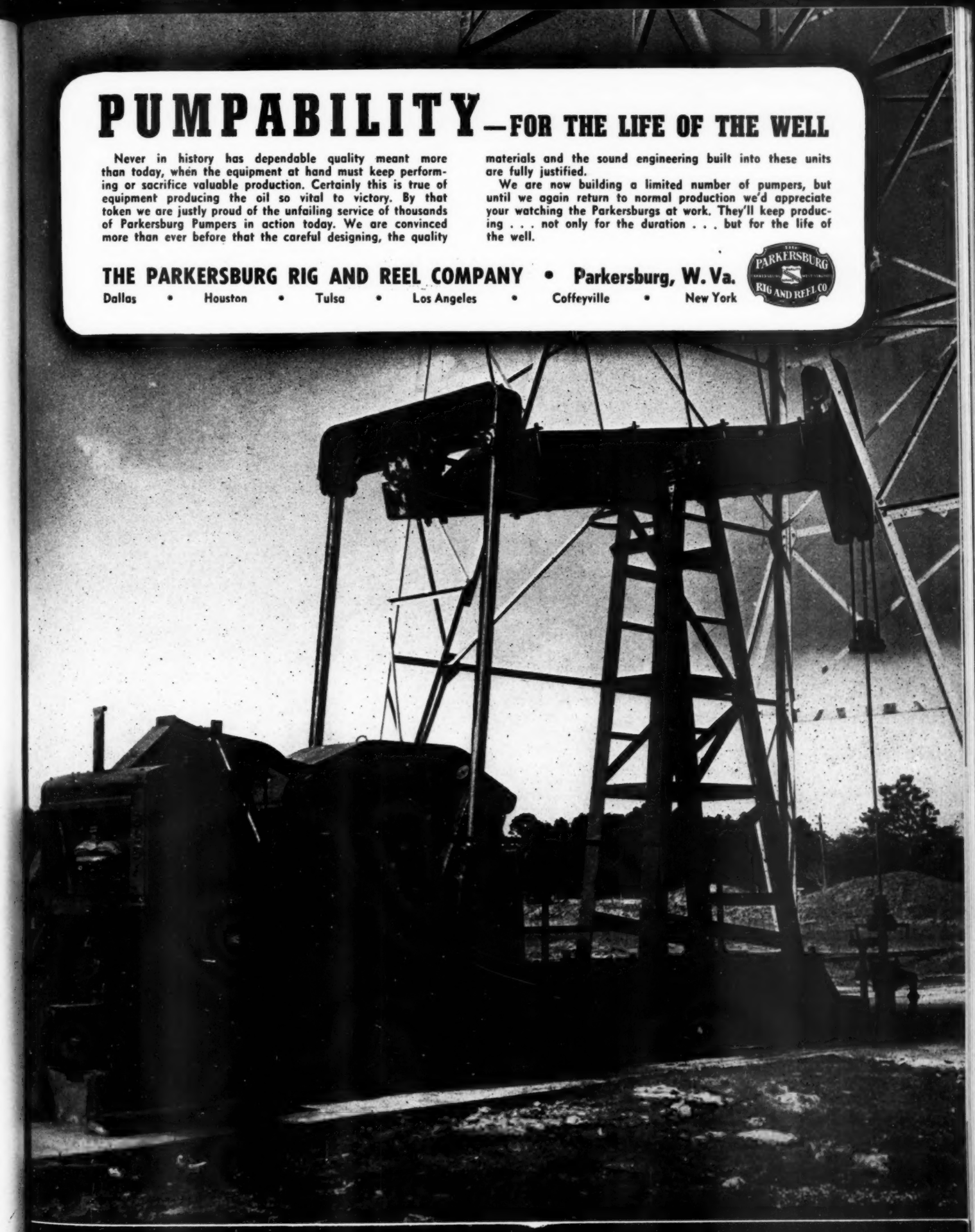
State	Number of fields	Number of projects	Area affected, acres	Number of producing wells	Number of injection wells
Air and gas repressuring					
New York		None			
Pennsylvania	26	63	4,725	1,640	480
West Virginia	29	34	52,200	3,066	291
Ohio	10	10	3,650	743	175
Kentucky	7	25	6,789	1,499	336
Illinois	12	24	10,180	1,066	264
Eastern total	84	156	77,544	8,014	1,546
Water-flooding					
New York	8	252	20,000	10,500	7,000
Pennsylvania	5	520	44,000	18,000	21,600
West Virginia	1	1	20	1	5
Ohio	2	11	270	144	189
Kentucky		None			
Illinois	3	14	4,110	357	247
Eastern total	19	798	68,400	29,002	29,041

*From Paul D. Torrey (ref. 1).

TABLE 2
Reconditioning methods used in Appalachian oil fields*

Type of work	Description	Results
1. Simple cleanout	Cleaning out cavings that may have covered the sand face	Fair production increase, especially where shale has caused cave
2. Shooting and cleaning out	Shooting pay with nitroglycerin to shatter sand, increase shot-hole size, burn off paraffin	Greatest production increase by this method
3. Steaming	Spraying face of sand with live steam to dissolve paraffin accumulation and clean the sand	Good temporary production increase until paraffin accumulates again
4. Chemical treatment	Dumping chemicals into a water-filled shot hole. Intense exothermic reaction that follows dissolves paraffin accumulation and cleans sand face	Good production increases in many places
5. Acidization	Acidizing Big Lime oölite pays with hydrochloric acid	Very effective in increasing production where porosity of pay is sufficiently high
6. Aquagel method	Pulling all or most of outside strings of pipe and substituting Aquagel mud	Reduces amount of steel per barrel of oil recovered. It is supposed to protect the production string from attack by salt-water corrosion. Not always feasible where casing is old and in a weakened condition
7. Water shutoff	Circulating cement (by a cementing service company) behind the pipe instead of running a smaller string of pipe on a packer	Reduces amount of steel per barrel of oil recovered. Not always feasible where casing is old and in a weakened condition
8. Deepening of wells	Drilling down to a deeper sand or drilling deeper in the same pay sand	Very effective in increasing gas reserves. At least two or three small but good oil fields are being developed in this manner. Many Oriskany gas wells are not drilled far into the sand initially because of their large volume. Substantial increases are noted a year or two later when the sand is drilled through

*From Douglas Rogers, Jr.



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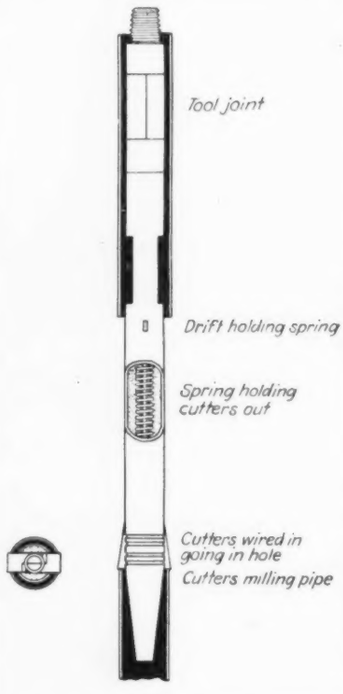


Fig. 3. Cable-tool underdigger

Caliper surveys have illustrated the tendency for shales to cave and for most sands and limes to maintain their drilled size. As electric logs are made for most wells, centralizer may be readily spaced in hard sand or lime formations. (Fig. 2). Pump plugs usually are used before and after the cement slurry. After cement has started around the shoe, vertical movement of the casing aids in reducing the possibility of cement channels.

Aluminum-base or low-carbon thin-walled steel casing is often referred to as "drillable metal." Tight or low-pressure zones that will not produce readily through ripped or perforated casing have often had windows of drillable metal to facilitate removal at a later date. Recently, when drillable metal was not obtainable, regular casing collars were spaced above or at the top of each prospective productive zone. This procedure often simplifies the removal of the casing opposite these pay sands.

Water analysis. Production data, drill-stem tests, core records and analysis, and electric log data are correlated and tabulated to establish water tables of the porous mediums of each field. Water analysis of true samples usually portrays some distinguishing factor of each zone. Chloride analysis, although simple and inexpensive, often gives sufficient information to determine from which formation a water originates. Table 3 lists data established in the New Harmony field, Illinois.

Being able to recognize the origin of water in multizone production areas is very important in performing successful remedial work.

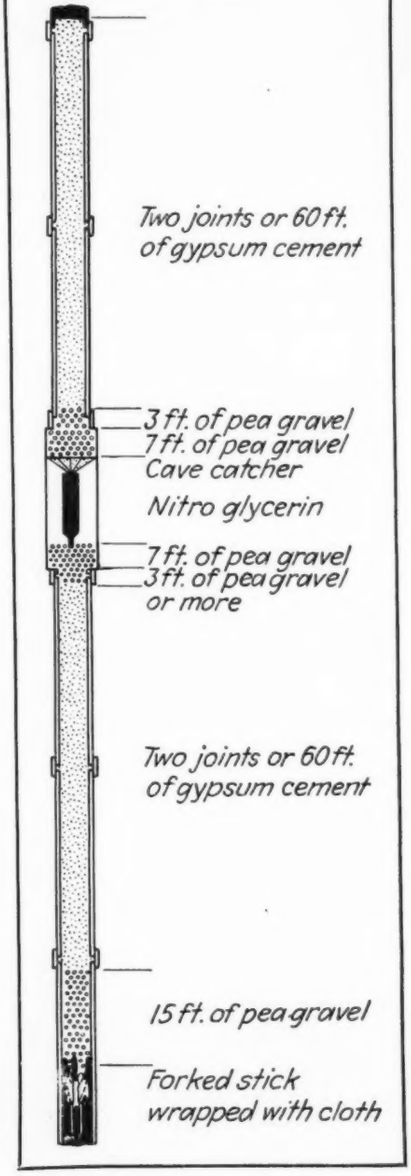
Opening upper sand zones. Cable-tool units are commonly used in the eastern states for "completions" and "workovers." Poor permeability, low bottom-hole pressures and sand conditions, are some of the reasons for the general choice of this equipment. Prior to pumping operations, wells often need shots to aid natural production, and need swabbing through the casing for cleansing. In most places only zones that test as thieves are abandoned when new zones are opened. In all known cases, the multiple zones are produced together and pumped from the deepest open formation.

Aluminum-base and low-carbon steel casing frequently are removed by using a cable-tool underdigger. (Fig. 3). The tool has two blades, which peen the pipe until it breaks off in chips. An open space between the uppermost end of the drillable pipe and its supporting collar enables the tool to start cutting quickly and correctly. The tool rotates with each stroke of the jars. A 20-ft. window can be removed, the cement behind the pipe cut out, and the formation underreamed in two days. Care should be taken not to feed this tool too rapidly, as it is possible to slot rather than remove all the casing. Cuttings can be removed from the open hole of a lower formation more easily than from over a bridge. When a bridge is necessary to protect the casing during a shot, the bridge should be placed after the reaming operation, as window cuttings tamped into the upper part of a bridge are difficult to remove.

Rotary milling cutters also are used for removing drillable windows. An impervious plug is set to protect the partly depleted lower zone. A bridging plug set with a wire line is suitable. When a shot is planned for the zone to be opened, a bridge is constructed. (Fig. 4). A forked stick with light wrappings of cloth is forced to 75 or 80 ft. below the proposed window by the stem of the drilling tools, 15 to 20 ft. of pea gravel is tamped above the forked stick and gypsum cement is placed 3 to 7 ft. below the bottom of the window. It is important that two joints (60 ft.) of casing be protected above and below a shot hole. The bottom-hole pressure of the open zones of a well must be in equilibrium at the time gypsum cement is placed. A 40-sec. A.P.I. viscosity mud consisting of one sack of Cementox to ten sacks of Aquagel usually will prevent drilling mud from penetrating the zone being opened. Reaming tools using more than two blades have proved most successful where tubing is used for drill pipe. A 20-ft. section of drillable pipe may be removed in 24 to 36 hours.

Regular steel casing can be removed successfully with rotary milling cutters. The operation is similar to removing drillable pipe, except that it is a slower process. Reaming tools with multiple sets of blades reduce the number of trips necessary with the drill pipe or tubing. Fig. 5 illustrates such a tool. Twenty feet of H-40 casing, 7 in..O.D. and 17 lb. per ft., can be removed in 5 days total time. Portable rigs using small drill pipe are adapted to such work. Auxiliary rotary tables operated by small high-speed motors frequently are used, the tubing from the well being used as the drill pipe. This rotary equipment, including kelly, swivel, rotary hose and mud pump, may be rented from service companies.

Fig. 4. Method of shooting a window


Two joints or 60 ft. of gypsum cement
3 ft. of pea gravel
7 ft. of pea gravel
Cave catcher
Nitro glycerin
7 ft. of pea gravel
3 ft. of pea gravel or more
Two joints or 60 ft. of gypsum cement
15 ft. of pea gravel
Forked stick wrapped with cloth

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Size—Fig. 141	Dimensions in Inches		Weight, Lb.
	Center to end	Center to top	
¼ & ⅜	1½	6½	2½
½	1⅞	7¾	4¾
¾	2⅛	9½	6¼
1	2⅜	10	13
1¼	2¾	12¼	19½
1½	3⅛	14¼	30½
2	3¾	16	40

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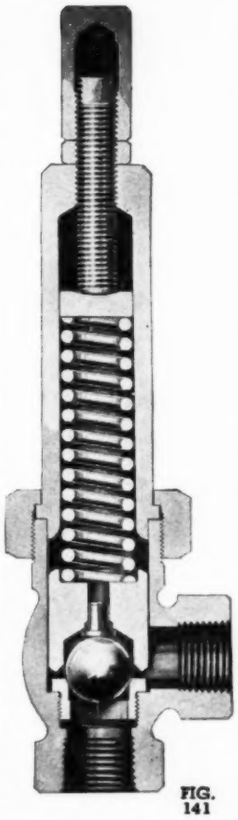

FIG. 141

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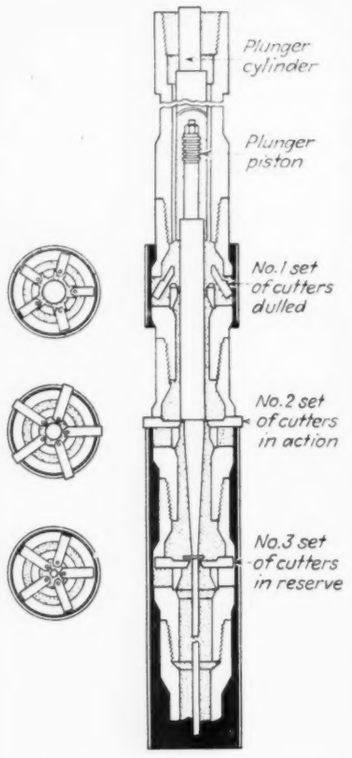

Fig. 5. Milling tool with multiple sets of cutters

Shooting a window. Some operators swab a reamed and underreamed well before shooting. This cleans the sand of mud cake and drilling water and possibly adds to the effectiveness of the shot. In rotary-reamed holes, the drilling fluid usually is displaced by clear water. As many operators tamp their shots with gypsum cement, the well should be in equilibrium at this time. In such cases little would be gained by swabbing a well prior to shooting. Most operators and shooters agree that the pipe over and below a window should be protected with approximately 3 ft. of pea gravel or sand. The shot should be placed at least 7 ft. from the top and bottom of a window. Fig. 4 illustrates one way of setting a shot in a window. In the newer production areas shots are often run in tin tubes rather than dumped or tamped into the hole. Solidified nitroglycerin is gaining in popularity over liquid nitroglycerin. Clock-operated time bombs are commonly used as detonator. Gravel or sand tamps are used by some operators. Regardless of the type of tamp, wells are filled to the top with water or oil before the time at which the shot is to go off.

In rotary drilling, the tamp or bridge of a shot hole offers little difficulty. Using cable tools for this operation necessitates care. Tools much smaller than the casing size eliminate some of the hazard. Best results in entering the casing below a shot hole are reported to be obtained by the use of a small sand pump. When it is necessary to use tools, single or double stem above a round-nosed bit, jars and sinker have given good results.

In some places shots have been used to remove drillable windows or regular casing. Difficulty is often experienced in entering the casing below the shot hole. It is believed a rotary reamer could perform this operation successfully. Research on this method, using cable-tool auxiliary portable rotary equipment, is being carried on at the present time. Shooting casing out of a well is successful and common where all lower zones are to be abandoned.

Ripping and gun-perforating casing to open upper zones has been used in almost all areas. Lime formations usually react nicely and produce readily through perforated casing. Lime formations also react favorably to hydrochloric acid treatments. Sand formations with permeability of less than 100 millidarcys ordinarily produce poorly through perforations. Table 4 shows composite data on reaming, shooting, and cleaning out upper sand zones.

Many operators are careful not to open too many windows in one well. These operators usually allow the deepest open zone to be shot, one window to be open and shot, and produce all other horizons through gun-perforated or ripped pipe. Many wells are known to have three and four windows open and to have been produced successfully for many months. The possibility of upper zones caving around the tubing of wells, which may cause the loss of deeper horizons, is the risk taken by operators of multizone wells.

Cypress sand wells of the Noble field, Illinois, ordinarily are completed by gun-perforating. In general, the first production from this field was from the McClosky lime. All the recent wells have been completed in the Cypress sand, and most of the McClosky wells have been plugged-back to the Cypress zone. New wells are drilled through the oil-water contact in the Cypress sand, which usually is 20 to 25 ft. below the top of sand. Casing is set with an average of 250 sacks of cement. Cement plug is drilled to below the oil-water contact point and 10 or 12 gun perforations are made at the contact point. One hundred sacks of cement are brought to location, yet usually only five or six sacks of cement can be forced into the formation with 2500 to 3000 lb. per sq. in. surface pressure. The top 2 or 3 ft. of the Cypress sand is then perforated 6 to 9 holes per ft. The permeability of the Cypress sand in one well was 350 millidarcys at the top. Some of the wells pump and flow 350 bbl. of oil per day initially. However, in a week's time wells usually are pumping 200 bbl. of oil and 300 bbl. of water per day. One company, which has 53 producing wells in the field, is injecting 15,000 bbl. of salt water per day in three disposal wells on the flank of the field. The injection systems are closed, the water is filtered and input pressures range near 200 lb. per sq. in.

Opening deeper horizons. When deeper production possibilities exist,

TABLE 3
Estimated water tables and chloride data,* New Harmony field, Illinois

Formation	Subsea depth, ft.	Chloride, P.P.M.
Waltersburg sand (main)	1,790	72,600
Tar Springs sand (main)	1,860	76,100
Cypress sand	2,240	107,200
Bethel sand	2,370	112,400
Aux Vases sand	2,490	126,300
McClosky lime:		
1st	2,515	133,700
2nd	2,535	135,800
3rd	2,577	138,400
4th	2,636	140,800

*Superior and Tide Water Associated Oil Company's Records.

TABLE 4
Reaming, shooting, and cleaning-out upper sand zones*

Data	Area A†		Area B†			
	Rotary reamer		Rotary reamer			Cable tool
	One window	Two windows	One window	Two windows	Three windows	One window
Number of jobs	35	9	4	5	2	6
Number of feet of casing milled	680	342	82	144	128	223
Feet milled*	19	38	21	29	64	37
Rotary cost*	$1167	$2166	$2134	$2443	$5707	None
Cable tool, shooting and cleaning out cost*	$1962	$3150	$2584	$1787	$3008	$5104
Total cost*	$3129	$5316	$4718	$4230	$8715	$5104
Average total cost per foot reamed	$ 164	$ 140	$ 225	$ 146	$ 136	$ 138
Production prior to workover, bbl. oil per day*	44 wells		56	18	38	47
Production after workover, bbl. per day*	107		163	110	138	114
Pay-out days*	154		61	56	128	134
	74					

*Confidential records of three oil companies operating in Illinois.
†Area A horizons all above 1800 ft.; area B horizons between 2500 and 2750 ft.
*Average per well.

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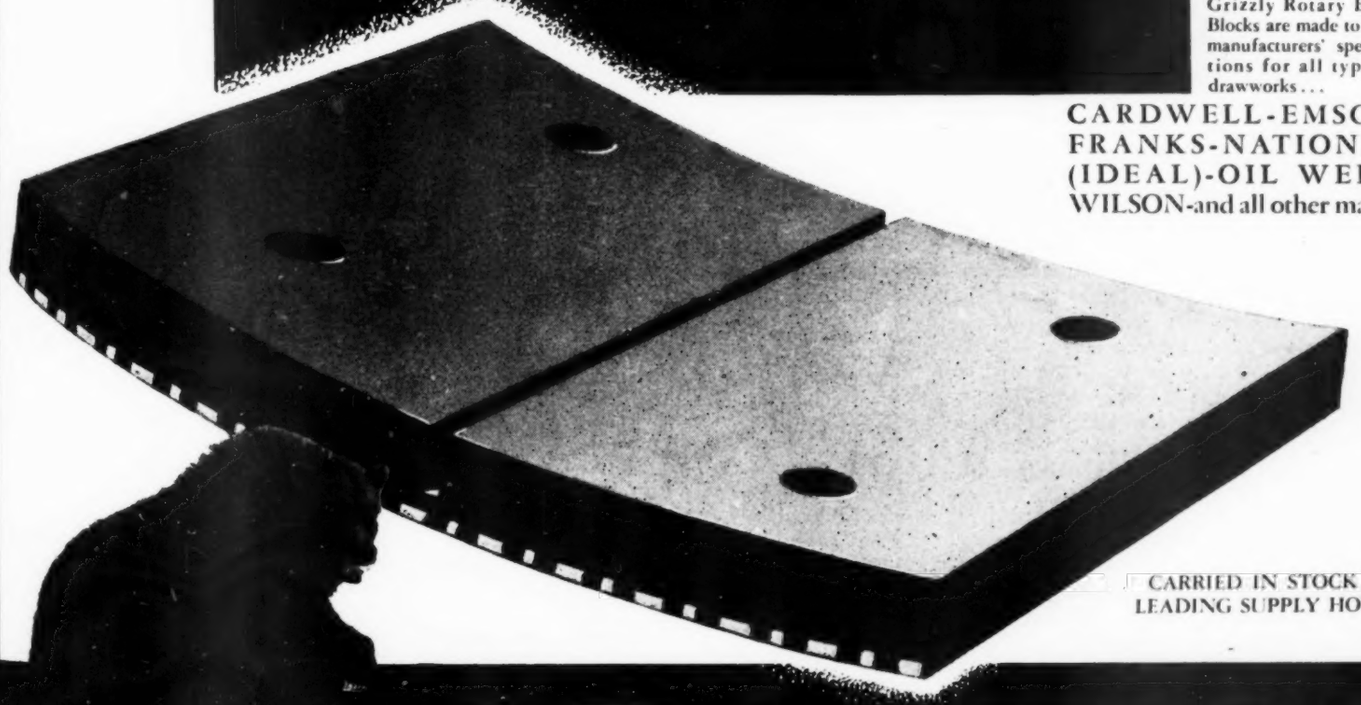

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most operators complete their wells with 6⅝-in. O.D. casing, or larger. The use of smaller casing makes a deepening operation hazardous and often impossible. It would seem feasible that one of the first tests in a field should be drilled through all the likely productive horizons. This would allow the planning of reasonable casing programs, well-spacing rules and production practices. It is more feasible and economical to open an upper formation than a deeper one. An original saving in tons of steel used does not always mean an ultimate saving.

Cable tools are used for deepening operations more often than rotary equipment, usually without trouble in hard sand or lime formations. When the formation stands up well two zones often are produced together from the open hole. When a caving condition exists, a liner is placed on a shoulder above the lower zone or a perforated liner set on bottom. The tops of liners sometimes are set in the casing, or even hook-walled to the casing. When water is produced between two formations, liners are cemented in place. Liners usually are cemented through tubing, using either a top-of-liner or bottom-of-liner release tool. In places where the upper formation has been shot, and it is desirable not to cement off this pay, a measured amount of cement is placed behind the liner. Blank liners set through a pay are gun-perforated.

When a well is to be deepened through known shale sections of any magnitude, or to a much greater depth, rotary tools have proved to be most economical. Several attempts at cable-tool deepening have ended with rotary completion, the combined expense being excessive.

In the Salem field, Illinois, 104 wells have been deepened from the Devonian lime to the Trenton lime. A combination of unusual conditions existed. The Devonian lime was cavernous and very porous, and in many places still produced 10 to 30 bbl. of oil per day. Operators desired to conserve this production. The Devonian pay had two or more breaks; for example, 3350 to 3370 ft. and 3400 to 3430 ft., shale possibly from 4280 to 4420 ft. and the Trenton lime was topped near 4600 ft. The 140-ft. shale zone caved readily during cable-tool operations. In a few places attempts were made to shut off the Devonian pay with acid-soluble cement, so as to obtain circulation for rotary deepening. However, these attempts were partial failures, and the wells were deepened with green bits, with very poor circulation, if any. All other wells were deepened with cable tools.

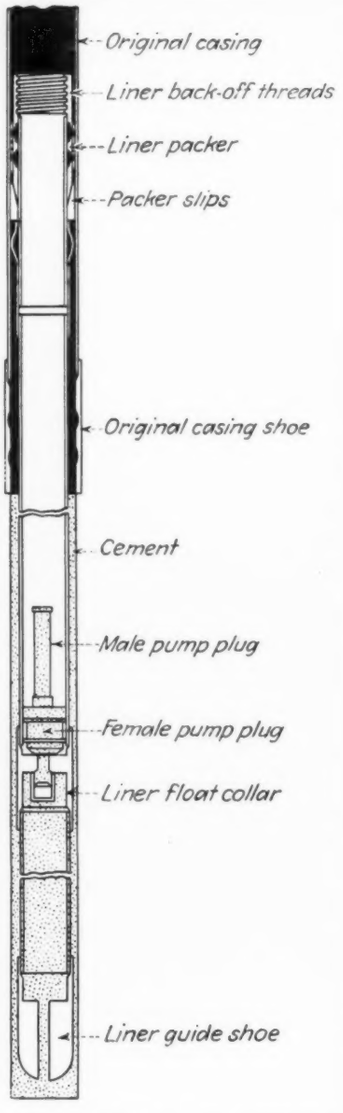

Fig. 6. Casing liner supported by hook-wall packer cemented through tubing, using male and female pump plugs

At first as long as 93 days was spent in recompleting a well, because of caving of the shale section. Attempts to cement off the shale cave were often failures. Best cable-tool results were obtained by packing the water course of the bit with Aquagel mud on each trip. Technique gained by experience cut the time needed for the recompletion to 25 days. Some of the wells would flow from the Trenton and if the Devonian was left open the oil would be taken by that formation. Often a 5-in. O.D. liner with collars turned down was hook-walled to the 7-in. O.D. casing, the liner being cemented through tubing, which supported it, from a back-off tool at the top of the liner. The dual female and male pump plugs were designed for this purpose. The female plug was set in the top of the liner and held with a shear ring. After the measured amount of cement was started down the tubing the male plug was inserted, and when it reached the female plug it would shut off circulation, shearing the ring of the female plug, which would follow the cement to the float collar of the liner. Fig. 6 illustrates this method of cementing a liner. The average Trenton well had an initial production of 100 bbl.; the better wells as much as 200 or 300 bbl. per day. Approximately 50 percent of the Devonian zones in the wells deepened have been reopened by gun-perforating. The wells are gun-perforated after the operator is sure that the production from both zones can be pumped from the lower horizon.

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2. C. R. Fettke: Water Flooding in New York and Pennsylvania. A.P.I. Secondary Recovery in the United States, chapter 3.
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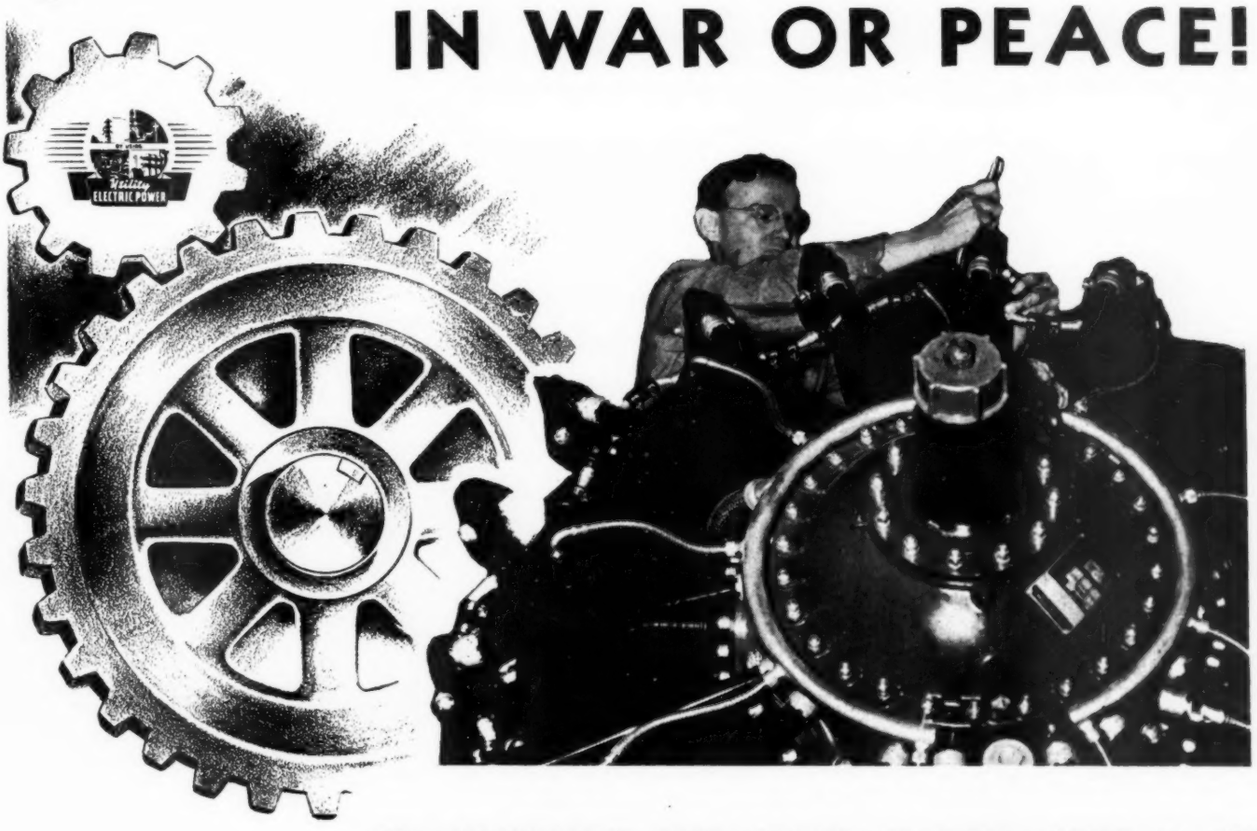

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Box 1498, Oklahoma City, Oklahoma

Performance Data on Enamel Type Pipe-Line Coatings[1]

By

WALTER F. ROGERS

Houston, Texas, Chemical Laboratory, Gulf Oil Corporation

A MAJOR pipe line company has installed at different times several makes of coal tar enamel and asbestos felt pipe-line coatings. The tests of the American Petroleum Institute on similar coatings have shown them to be subject to soil stress and clod indentation. Such areas as well as those of incomplete application or "holidays" are those at which soil corrosion will develop. Because of these sources of penetration, pipe coatings alone cannot be relied upon for complete metal protection. Electrical drainage must be used in addition to the coating for complete success.

The amount of electrical current required is governed by the resistance of the coating and the size of the exposed pipe areas. As the resistance of these hot applied coal tar coatings is usually very high the current required is governed largely by the exposed areas.

During the latter part of 1941 a series of tests were made to determine the electrical resistance of the enamel type coatings in use by the company. The ages of the coatings varied from 14.2 months to 12 years. These tests were considered advisable to determine the effect of several variables in the method of application of the coatings, the differences among the different brands of coatings used, and the quantity of electrical current required to protect pipe so coated. Some of these coatings had been tested several times previously and additional data on the effect of underground aging were desired.

[1]Presented at National Bureau of Standards' Soil Corrosion Conference, St. Louis, Missouri, March 25, 26, and 27, 1943.

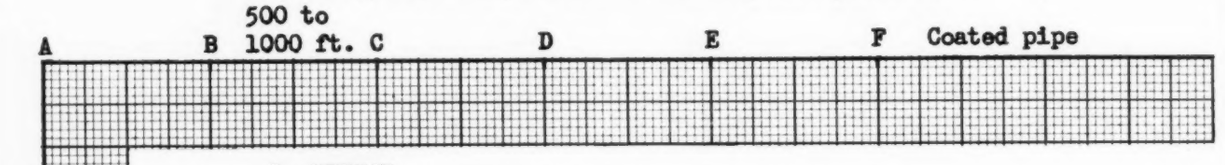
Method of Test

The test data obtained were the current picked up by the coated pipe and the voltage drop across the coating. From these measurements of (E) and (I) the value of the corresponding resistance is calculated. Fig. 1 shows the diagram of a typical setup and the method of calculation.

The actual technique required a ground bed, a welding machine for d-c. current output, a copper sulphate electrode and a 0 to 4 volt potentiometer. The ground bed was constructed by placing 10 ft. of 6-in. pipe in a 2-ft. wide ditch, 18 in. deep. The ditch was a minimum of 20 ft. from the pipe line to be tested. The soil was back-filled along with 500 lb. of salt and the remaining voids filled with water. The positive cable of the welding machine was connected to the ground bed and the negative side to the coated pipe. The arrangement of pipe and salt gave a ground resistance resulting in current outputs of 9 to 50 amp. The variation was due largely to the short time allowed for the soil to become salt soaked in the case of the 9 amp. output. The welding machine voltage in these cases was 40 volts. The amount of current required for this type of test varies with the number and distribution of pipes in the right-of-way but must be of sufficient strength to give a minimum 5.0 mv. potential drop along 100 ft. of pipe at the drain point.

While the current was alternately flowed to the pipe and cut off at 5-minute intervals measurements were made along the coated line. The measurements were taken at intervals of 500 ft. to 1320 ft. The greater the coating resistance the greater the distance required between readings to get a change in value greater than the precision of the readings. The measurements made at each location were the pipe-to-soil

Fig. 1. Apparatus and procedure for measuring coating resistance



1. METHOD
At A,B,C, etc. measure pipe to soil potentials with test current on and off. Also measure current in pipe with test current on and off.

2. CALCULATIONS

Location	Soil-pipe potential (volts)				Line current (amp.)			Place		Resistance	
	No. I	With I	ΔP	Av.ΔP	No. I	With I	ΔI			ohms Av.ΔP / I	ohms/ft. Xohms
A	0.50	0.95	0.45		0	1.00					
				0.425			0.05	A-B		8.5	8500
B	0.50	0.90	0.40		0	0.95					
				0.375			0.05	B-C		7.5	7500
C	0.50	0.85	0.35		0	0.90					
				0.325			0.05	C-D		6.5	6500
D	0.50	0.80	0.30		0	0.85					

Ground Bed

X = Distance A to B. Taken as 1000 ft.

HE GAVE HIS LIFE

We are asked only to LEND our money

JIMMIE was a lovable, laughing youngster with all the world to live for. His mom was a peach, his dad a pal, and his girl so sweet he could hardly believe that she preferred his company to that of wealthier, smoother and more attractive lads.

Saturday, December 6, 1941, Jimmie had the time of his life at a school dance. Sunday, December 7, he was glued to his radio. Monday, December 8, he was a member of the United States Army.

Jimmie stood up bravely under the hardships of training — but he couldn't stand up under the sharp, hot impact of a sniper's bullet.

Let's keep the picture of Jimmie in mind when we decide how much of our money we can invest in war bonds. His stake in America was no bigger than ours, his responsibility no greater. He gave his life. Can we do less than go the absolute limit in providing the things that Jimmie's buddies need to finish quickly the job they have started?

Sacrifice? Can any investment be called a sacrifice that is backed by the resources of the world's wealthiest nation? Is it a sacrifice to lend money with the assurance that it will be repaid with interest? Sacrifice? Let's ask Jimmie's parents the meaning of the word!

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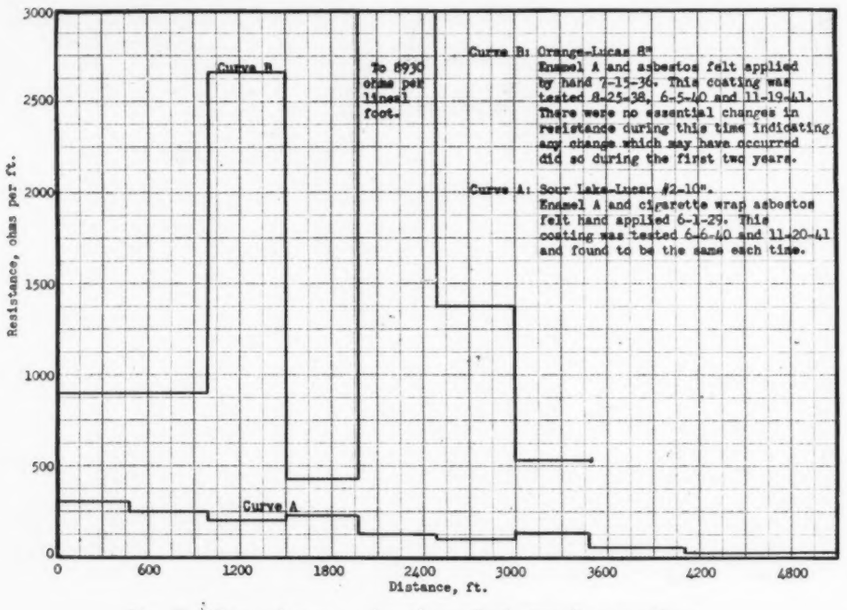

Curve B: Orange-Lucas 8"
Enamel A and asbestos felt applied by hand 7-15-36. This coating was tested 8-25-38, 6-5-40 and 11-19-41. There were no essential changes in resistance during this time indicating any change which may have occurred did so during the first two years.
Curve A: Sour Lake-Lucas #2-10".
Enamel A and cigarette wrap asbestos felt hand applied 6-1-29. This coating was tested 6-6-40 and 11-20-41 and found to be the same each time.
Curve B
To 8930 ohms per lineal foot.
Curve A
Resistance, ohms per ft.
Distance, ft.
0
500
1000
1500
2000
2500
3000
600
1200
1800
2400
3600
4200
4800

Fig. 2. Effect of age on hand-applied pipe-line coatings

potential using a copper sulphate reference electrode and the voltage drop along 100 ft. of the pipe. The measurements were made at each place both with the current flowing and with it off. Contact was made to the pipe with heavy, sharp-pointed steel bars. These measurements completed the field work and the remaining calculations were made later. The time for a crew of four men to drive to the location, install the ground bed, take the readings, remove the ground bed, and return to the station varied from 6 to 8 hours.

The data were obtained on five different lines. The same data had been obtained previously on three of these lines at least one time and for one of them twice.

Data

For best comparison the data have been divided into three groups. These are illustrated in Figs. 2 to 4.

Fig. 2 shows the condition of two sections of enamel A and asbestos felt applied by hand.

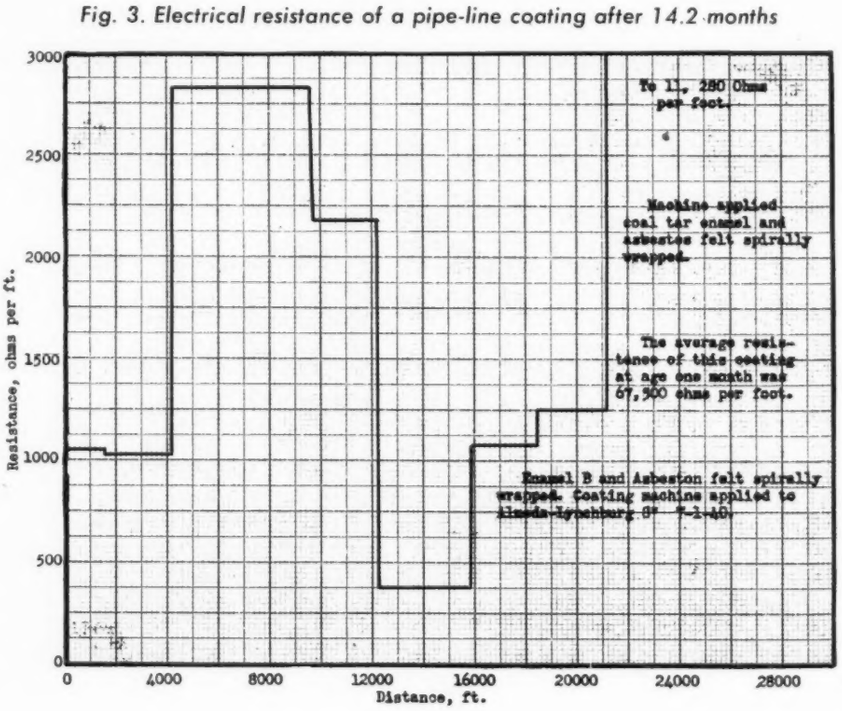
Curve A shows the condition of the enamel on the Sour Lake-Lucas No. 2, 10-in. line eleven and one-half years after being applied. When this coating was installed the asbestos felt was applied by being wrapped lengthwise or cigarette fashion around the pipe. Later practice developed the spiral direction of application now used almost exclusively. Reference to the curve shows that the resistance of the coating was calculated in units of 500 ft. each. The resistance values are quite low and vary from 25 to 300 ohms per lineal ft. Pipe of 25 ohms per ft. resistance in this soil is practically bare. Resistance values greater than 25 ohms per ft. show the presence of greater quantities of coating. On June 6, 1940, or a year and five months earlier, the resistance of this same section of coating had been determined. The results at that time were identical with those of the later test. This shows the coating breakdown had occurred prior to the 1940 inspection.

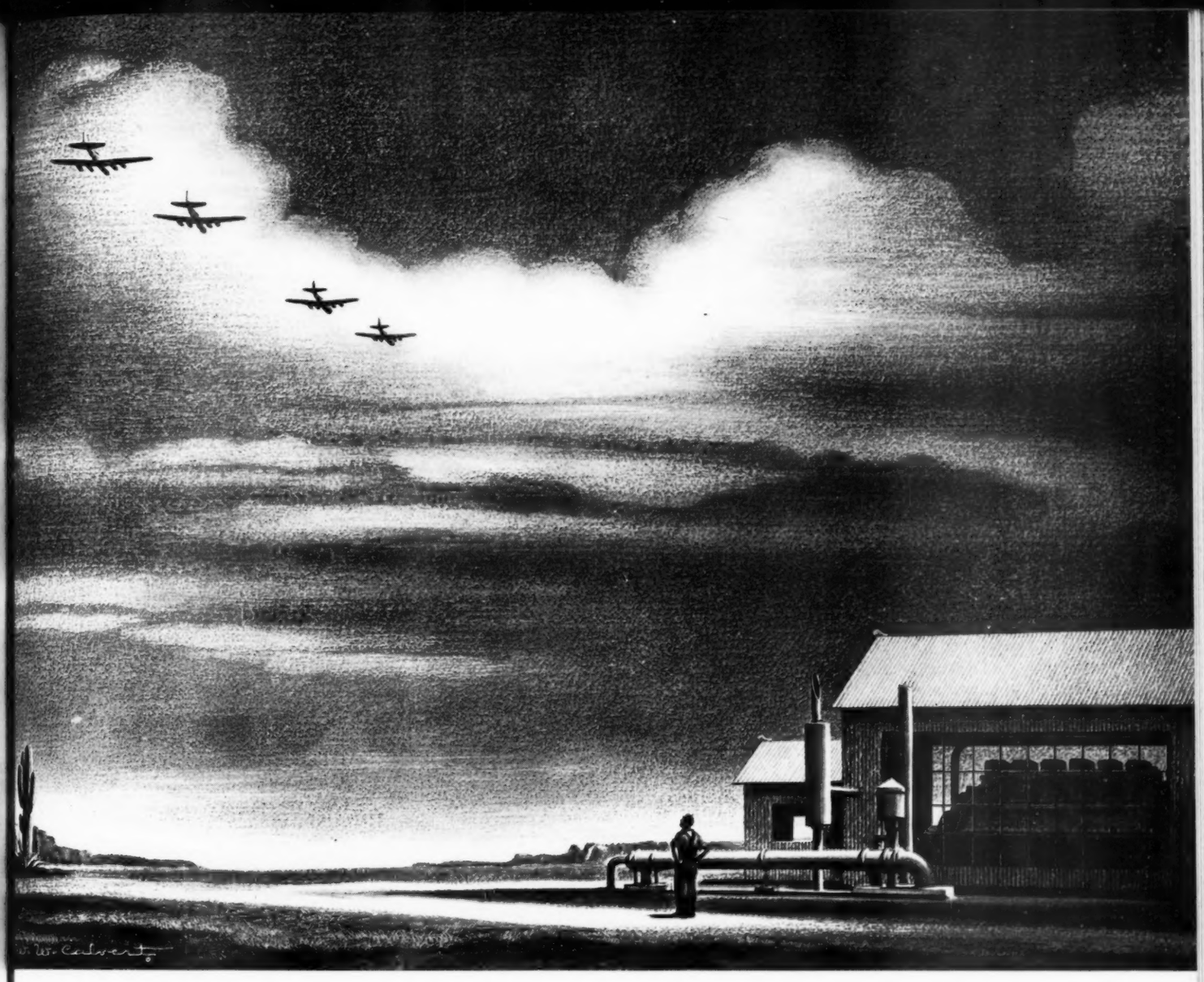
Curve B shows the condition of the same brand of enamel, hand applied but with a spiral wrap of asbestos felt applied to the Orange-Lucas 8-in. line. This coating lies through a wet marshy soil where corrosion rates are very high but soil stress and clod indentation of the coating is low. This coating was applied in 1936 and was tested after 25 months, 47 months, and 65 months. No essential changes in the coating resistance were found during these three test periods. This shows that any coating break-down that occurred did so during the first 25 months after the coating was applied. It will be noted that the coating resistance varies from 425 to 8930 ohms per lineal ft. This is both a considerable range in coating resistance and a considerable increase in resistance over the maximum for the other line with the same but older coating. The increased resistance is believed to be due both to better application of the coating and to the greater serviceability obtained from the spirally applied asbestos felt.

As both these coatings show resistances sufficiently low to indicate soil contact from any one of the numerous possibilities it is advisable to calculate the quantity of current required for protection of the exposed areas. The minimum current required is that sufficient to give a potential drop through the coating of 0.30 volts, which will usually bring the total pipe potential as measured to a copper sulphate reference electrode to 0.85 volts.

The potential drop through the coat-

Fig. 3. Electrical resistance of a pipe-line coating after 14.2 months





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Lonely landmark of a vast underground network of oil pipe lines, the pumping station stands as a vital link in America's oil transportation system. Like a pulsing heart its diesel engine keeps the nation's life blood flowing, night and day, toward coastal areas where, without this precious resource, planes and ships would be bound to earth and shore, war industries and workers reduced to ineffectiveness.

First oil engine to be placed in trunk pipe line service was a De La Vergne. This was in 1907. First in the entire petroleum industry was a De La Vergne in 1905. These engines were the pioneers of hundreds of diesels, now built by Baldwin, which are providing the pipe lines with proven, dependable power.

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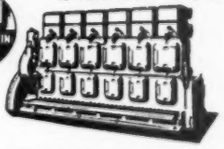

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ing at any place along the line can be calculated from the expression:

$$E = \sqrt{AK}\ Io\ e^{-\alpha x}$$

Where:

E = the voltage to soil at any place,

Io = the current in the pipe at the drain,

e = base of natural logs,

$$\alpha = \sqrt{\frac{A}{K}}$$

A = resistance of the pipe in ohms per ft.,

K = Resistance of the coating or soil. If the soil resistivity in ohm-ft. is used this value must be corrected to the resistance of the annular region between the pipe and the copper sulphate electrode by the expression $K = 0.21\rho$ where ρ is the resistivity of the soil, and the pipe center depth is 20 in.

Using this expression and taking the average resistance of the coating in Curve A as 100 ohms per ft. it is found that 10 amp. will protect the pipe for one-half mile provided a second power source is situated one mile on each side of this first unit.

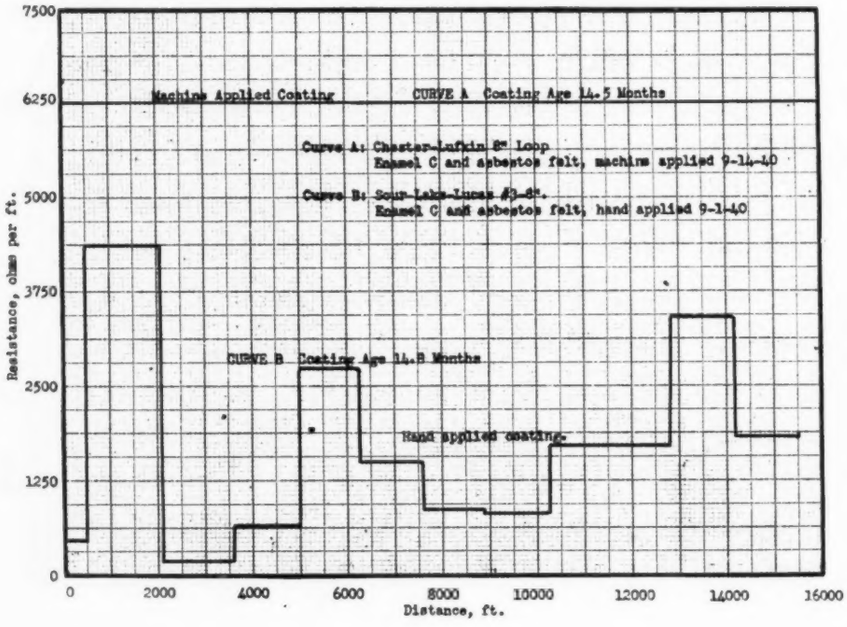
The resistance values for Curve B are so high that the electrical protection could be designed on the minimum resistance of 425 ohms per ft. This coating can be protected for approximately 3 amp. per mile.

Fig. 3 shows the condition after 14.2 months underground of approximately five and one-half miles of enamel B and asbestos felt spirally wrapped. This coating was applied by machine during July, 1940. The following month the resistance of this coating was determined and found to be 67,500 ohms per ft. This is an extremely high resistance and 15 amp. protected about 25 miles of the coating. After 14.2 months burial the resistance was redetermined over six miles of the coating. The resistance was found to have dropped to between 375 and 11,280 ohms per ft. These resistance values are still quite ample as these five and one-half miles of pipe are being thoroughly protected with 17 amp. or 3.1 amp. per mile. This could be decreased to 2.0 amp. per mile if only the minimum required rise in voltage was desired.

Fig. 4 shows the condition of two sections of enamel C after 14.5 to 14.8 months burial. The amounts of coated pipe tested in each case were approximately three miles. Curve A shows the resistance obtained for the machine applied coated section. The resistance curve is quite level and has the average value of 6250 ohms per ft. This stretch of coating lies through well drained predominantly sandy soils of high resistance. This soil resistance is included in the 6250 ohms per ft. but even excluding the soil resistance only reduces the coating value to about 6000 ohms per ft. This stretch of coating could be protected with 1.0 amp. per mile.

Curve B shows the resistance of a three-mile section of the same coating applied by hand. Although this stretch of the coating is only 0.3 months older than the first the resistance values are much less. These vary from 4375 to 150 ohms per ft. with an average value of 1280 ohms per ft.. Undoubtedly some of the difference in resistance between the two sections of coating is due to the difference in method of application as it is to be expected that the machine-applied job would be the better. The soils, however, along the hand-applied stretch are more clayey and drainage is poorer than for the machine-applied section and this undoubtedly has contributed some to the lower resistance. The enamel of Fig. 2 was machine-applied in a soil very similar to this one. The average resistance value for this coating is 4223 ohms per ft. This final higher resistance value over the hand applied coating value of 1280 ohms per ft. must be the result of the application method. Despite its relatively low resistance the hand-applied section can be protected for about 2.5 amp. per mile.

Fig. 4. Effect of age on hand- and machine-applied pipe-line coatings



Discussion of Data

These data were obtained to determine primarily four things about pipeline coatings. These were:

1. The difference between brands of coal tar enamels.
2. The rate of breakdown of these enamel coatings when wrapped with asbestos felt.
3. The difference between hand- and machine-applied coatings.
4. The electrical current required for protection of coated pipe.

Although the data of this study were not all determined under identical soil conditions the conclusions are drawn as though they were and it is not felt that the variations of soil properties are sufficient to invalidate these conclusions.

1. Judging between the two sections of machine-applied enamel C and enamel B there is no essential difference in the performance of the two coatings and at equal price per gal. are of equal value.
2. These enamel coatings experience a large drop in resistance during their first year underground. The rate of drop after this time is relatively slow.
3. The hand-applied coatings with spirally wrapped asbestos felt have average resistance values of 2246 and 1280 ohms per ft. The two machine-applied coatings have average resistance values of 6250 and 4223 ohms per ft.
4. The electrical current required for protection of coated pipe is a complex function of the pipe resistance. In general the hand-applied coatings may be protected for about 3 amp. per mile whereas about 1 amp. per mile is required for machine-applied coatings.

Acknowledgment

The writer wishes to thank the executive department of the Gulf Oil Corporation-Gulf Production Division for their kind permission to publish these data.

☆ ☆ ☆

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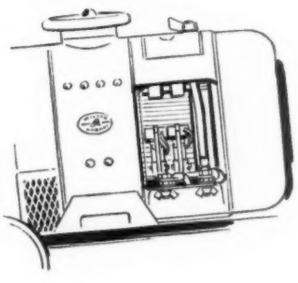
3 Be sure that bearings are properly greased. Refer to manufacturer's operating instructions for correct procedure and recommended lubricants.

4 Check all connections regularly to insure perfect contact. Loose connections may cause erratic operation.



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IDLE CYLINDERS ARE PRODUCTION SLACKERS: KEEP 'EM ROLLING FOR VICTORY!

The Determination of the Current Required for Cathodic Protection*

By KIRK H. LOGAN, *National Bureau of Standards*
In collaboration with
J. M. PEARSON, I. A. DENISON, R. F. HADLEY, and A. V. SMITH

Abstract

EXPERIENCE has shown that cathodic protection can be used successfully and economically to reduce or prevent the corrosion of buried structures. Several criteria for determining the amount of current required to protect a structure are in use, most of which are based only on experience. A method based on scientific measurements has been developed. This paper points out the unreliability of the older methods of determining when a structure is protected against corrosion and presents methods and describes apparatus for applying the more scientific criterion for protection. Examples of the application of the new methods are given and the required apparatus is so described that it can be constructed.

Introduction

Cathodic protection was suggested by Sir Humphrey Davey[1] in 1825, and has been discussed and practiced extensively and in various ways since that time. The author's incomplete file of recent articles on this subject contains about 130 listings, and 19 additional articles on the subject were prepared for the 1943 Bureau of Standards Soil-Corrosion Conference.

The extent of the practice in 1939 was indicated in an article by Scherer,[2] whose study of the subject indicated that 26 pipe-line operators had installed 542 cathodic protection units to protect 2000 miles of pipe lines.

A review of the literature on cathodic protection indicates that most operators of cathodic protection systems are convinced that they have substantially reduced, if not completely eliminated, corrosion in an economical way. This is a good indication that cathodic protection as generally installed is reasonably satisfactory.

There is, however, a considerable difference of opinion regarding how the current required for protection should be determined and there are very few specific scientific data on this subject. The criteria commonly used are empirical and are unsupported by adequately accurate records or data. Experience unquestionably shows that most well-maintained installations for cathodic protection have substantially reduced the rate at which leaks appeared, but short-period leak records are inadequate to show whether corrosion has been entirely eliminated or whether corrosion might have been prevented with much less current.

*Presented before National Bureau of Standards' Soil Corrosion Conference, St. Louis, Missouri, March 25-27, 1943.

Cathodic Protection Criteria

1. **Pipe potentials.** Cathodic protection depends upon the maintenance of each part of the steel surface at a potential sufficiently negative to prevent it from acting as an anode with respect to any other part of the system. To maintain this value of the potential in the prevailing environment it is necessary to apply to the steel structure continuously a certain minimum current. This current is a function not only of the environment, but also of the area of steel to be protected; in other words a certain minimum or average current density must be applied. If the cathodic surface is definite and measurable, and is at a uniform potential with respect to the environment and the anodes employed, the current density may be computed from the current or vice versa. However, if on the pipe lines, a large part of the steel surface is insulated, current can flow only to small areas not easily defined or measured. Even with a bare steel pipe the use of any practicable arrangement of anodes will result at best in only an approximate uniformity of the potential of the pipe and of the resultant current density. Hence any computations of current density from the applied current represent at best average current densities, and give no direct evidence of the distribution of current on the structure. Although in the following discussion, reference will usually be made to the measurement of current, it should be clearly understood that the determining factor is the current density, even though it cannot usually be computed with high accuracy.

It is generally agreed and can be shown by the consideration of electrochemical principles that electrolytic corrosion of steel will cease when current flows to all points on the surface of steel. The difficulty in determining whether this condition has been established with respect to a buried metal lies in the facts that neither the buried metal nor the soil adjacent to it is an equipotential surface. As a result, measurements of the difference of potential between the metal and the earth, taken to determine the direction of the current in the earth with respect to the surface of the metal, represent the average of several potential differences which may differ in magnitude and direction. Therefore, the cathodic-protection engineer usually tries to apply a potential which will cause at least some current to flow to every point on the metal surface. As he has no way of determining when he has accomplished this he is forced to apply such potentials as experience has shown to be satisfac-

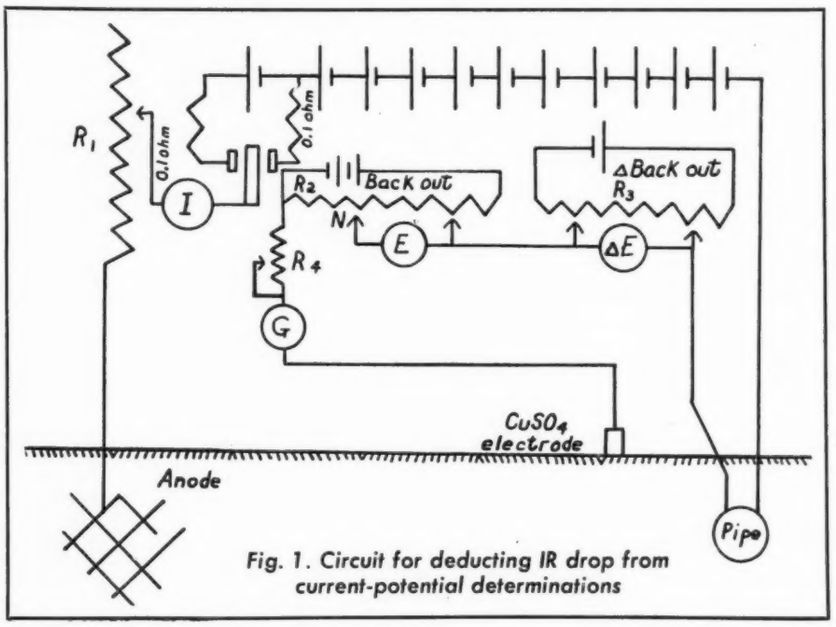

Fig. 1. Circuit for deducting IR drop from current-potential determinations

then I said to myself—

So . . . the Nazis couldn't sink her!

This 12,500-ton, all-welded tanker "Victoria" was torpedoed amidships. Her deck plates buckled but her bulkheads held. Then, the baffled Nazis smashed a second torpedo into her and left, confident she was finished. But those welds refused to yield—even to Nazi TNT. She made it to port and was repaired—ready for the subs again. Some ship, I say!

Some construction, you mean! This is just one of many welded ships that have refused to be licked by torpedoes. Just like our welded M-4 tanks which withstood the Nazi 88's in North Africa. Ships, tanks, planes and guns—they're all welded for strength as well as for savings in time and materials.

Better products and *lower costs*—just what I want in my business after the war. Then why shouldn't I weld my peace-time products?

You should! You MUST if you plan to survive in the face of war-developed ideas. And believe me, your ship of business will sink or float, depending on how well you can stand up against competition on WELDING ECONOMY. Why not start NOW to learn from Lincoln the latest kinks in welding thrift.

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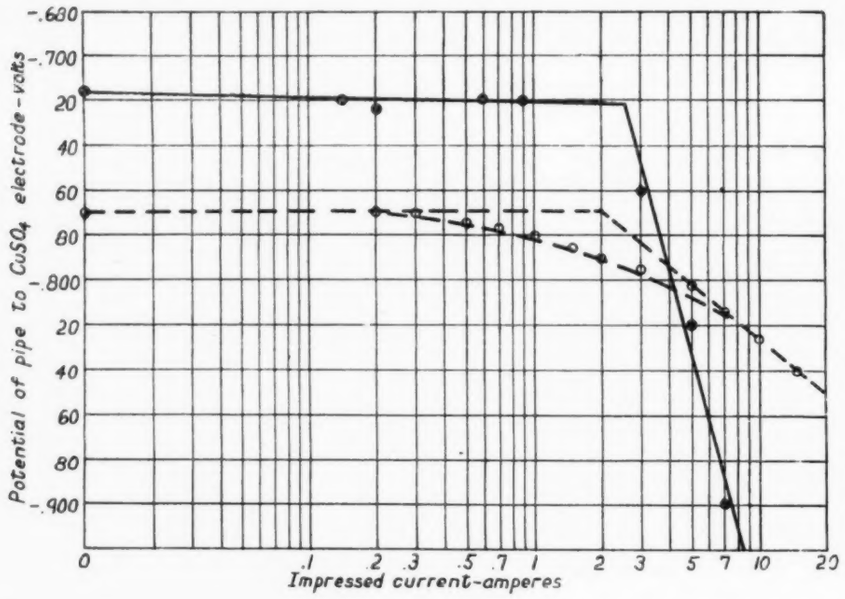

Fig. 2. Current-potential curve—IR drop deducted

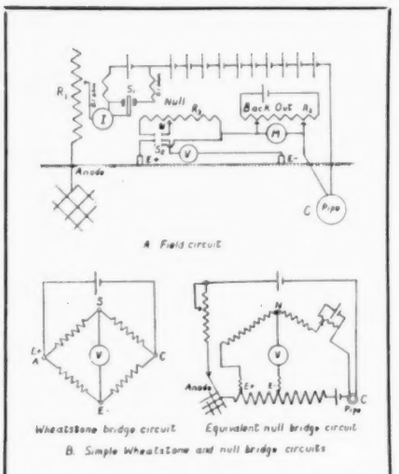

Fig. 3. Pearson-Hadley null circuit

tory under other conditions assumed to be similar to those under consideration. The simplest of these procedures is to apply current until the pipe is negative to the earth by an amount depending on the kind of electrode used and the judgment of the engineer. Three-tenths of a volt is the difference of potential frequently chosen if a steel electrode surrounded by the same soil is used, and 0.85 volt if the reference electrode is copper surrounded by a saturated copper sulphate solution.

The copper-copper sulphate electrode is frequently regarded as preferable because it is nearly constant in its potential and nearly free from polarization if it carries only a very small current.

That the potential of iron with respect to a copper sulphate reference electrode is not the same for all soils is indicated by Table 1. For a test of the effectiveness of zinc as a source of cathodic protection, three iron rings were buried in each of eight locations. The potential of each ring, relative to a copper-sulphate electrode, was measured with a potentiometer voltmeter before the experiment was begun. The potentials at six of the test sites are shown in Table 1.

TABLE I

Location	Potential of iron ring with respect to Cu SO_4 electrode, volts
Austintown, Ohio	—0.575 to —0.600
Deerfield, Ohio	—0.725 to —0.730
Rocky Ford, California	—0.740
Albuquerque, New Mexico	—0.70 to —0.74
Los Angeles, California	—0.49 to —0.52
Shreveport, Louisiana	—0.754 to —0.760

The current-potential curves to be presented later in this paper also indicate that pipes do not have a definite potential with respect to a reference electrode. Gatty and Spooner[3] have shown that increasing the supply of oxygen renders less negative the potential of iron immersed in an electrolyte. They have also shown that increasing the alkalinity of the solution in which iron is immersed makes the potential of the iron more negative. As soils differ greatly in aeration and in pH values, it is to be expected that the potential of buried pipe may differ considerably in different soils.

The total measured potential difference between a pipe and an electrode some distance from its surface may include an IR drop caused by current flowing to or from the pipe. This factor may obscure differences in the true potential. On account of the possible sources of error just mentioned many engineers use the change in potential of the pipe when current is applied as the criterion for the degree of protection and assume that the pipe is protected when its potential has been lowered 0.3 volt. Obviously, the condition of the pipe may be such that no current is required for its protection, in which case the lowering of its potential is unnecessary. Under other conditions the change in potential of the pipe with respect to an electrode some distance away may be due largely to the IR drop in the soil and not be representative of the potential change at the pipe surface. To avoid this error some engineers use an electrode separated from the pipe by about ⅛ in. of insulation. This avoids most of the IR drop unless the pipe has an insulating coating, but such measurements are influenced by the condition of the pipe adjacent to the electrode. It is, of course, possible to take account of the resistance of the soil or coating surrounding the pipe, as has been done by Ewing[4] and Scott.[5,6] The most important objection to using the potential or the change in potential as a criterion for protection was pointed out by Ewing,[7] who showed that when current was applied to a cathode such as a pipe line the potential of the protected metal with respect to a reference electrode might gradually increase or decrease, depending on the reaction at

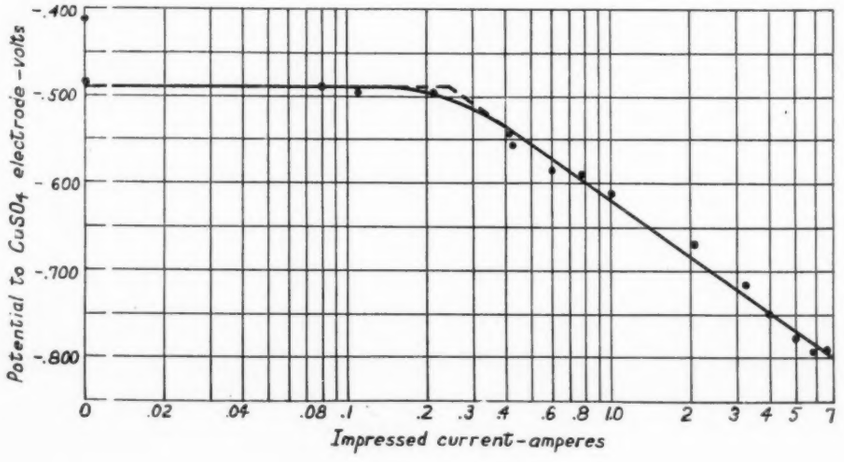

Fig. 4. Current-potential curve for 16-in. pipe

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the cathode, which reaction is determined by the aeration and pH value of the soil.

2. **Current-potential curves.** In the course of a study of the velocity of corrosion Britton[8] found that when the current flowing to a piece of iron in aerated 1/10 *N* potassium chloride solution was gradually reduced from a value more than sufficient to prevent corrosion of the iron, the potential of the iron with respect to a reference electrode quite near it became more positive down to a certain current, and then remained constant as the current was further reduced. Experiments as well as theoretical considerations showed that the break in the potential curve occurred at the current density just sufficient to prevent corrosion. The experiment was repeated with other concentrations of potassium chloride and 1/10 *N* potassium sulphate. Ewing,[7] working at the Bureau of Standards as a research associate for the American Gas Association, undertook an extended investigation to determine how the phenomenon discovered by Britton[8] could be used to determine the current required for the protection of pipe lines. By using the work of Muller[9] he showed that the true potential of a corroding cathode was its measured potential diminished by the IR drops resulting from the flow of the local and imposed currents, i.e., that if these IR drops were deducted or eliminated from the observed values, the corrected potential of the cathode would be a constant. Ewing also showed by reasoning and citations of the work of other experimenters[9, 10] that, after the current became sufficient to prevent corrosion, the cathode would act as a hydrogen electrode, the potential of which varies with the logarithm of the current flowing to the cathode. Consequently if the true potential of the cathode is plotted against the logarithm of the impressed current the resultant curve should consist of a horizontal and a sloping line, connected by a curve representing the transition to the overvoltage curve. The intersection of the projections of the straight lines indicates the current required to reverse the potential of all anodic areas, i.e., the current required to prevent corrosion. If the resistance of the electrolyte is low, sharp breaks in the current-potential curves can be obtained, as was done by Britton without considering the IR drop. With high-resistance electrolytes a smooth curve with no break is obtained (see Fig. 6) if the measured potential is not corrected for IR drop. Several laboratory methods for making this correction or for eliminating the IR drop have been developed,[11] with which Ewing and Denison[12] have obtained satisfactory curves for soils in the laboratory. The apparatus that they used is unsuitable for field work in which large currents are involved.

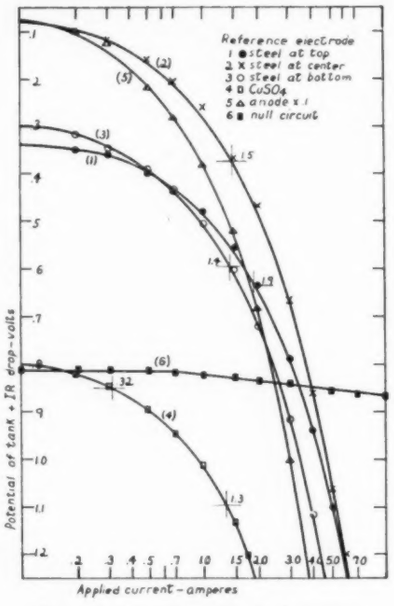
Reference electrode
1 ● steel at top
2 X steel at center
3 ○ steel at bottom
4 □ CuSO4
5 △ anode x 1
6 ■ null circuit
Potential of tank + IR drop - volts
Applied current - amperes

Fig. 6. Current-potential curves for tank

Considerable space has been given to the various criteria for protection and the methods for their application and references to the researches of several scientists have been cited because the safety of large investments in cathodic protection depends on the validity of the assumptions upon which the design of the protective systems has been based. It will be shown that the use of different criteria may result in wide differences in the estimated values of the required current and that either too much or too little current may be supplied, depending on the criterion for protection chosen in the design of the protective system. Relative ease, speed, and cost of determining the required current can be considered only after the reliability of the data resulting from the determination has been established.

Determining Current

1. **Apparatus common to all methods.** All methods for determining the conditions required for the protection of a buried structure involve a source of electrical energy such as a welding generator, rectifier or battery; a means of varying the current, such as a rheostat, and an ammeter. The sizes of these pieces of apparatus depend on the size and condition of the structure to be protected. Usually considerably more current will be required for a test based on Ewing's criterion than for the other methods, although the current required for protection may be less according to Ewing's criterion. All methods involve the measurement of the potential of the structure with respect to a reference electrode, and because of the high resistance of this electrode or of the earth adjacent to it and because of the possibility of polarization of the electrode, the potential measuring instrument should have a high internal resistance. A potentiometer-voltmeter or a vacuum tube voltmeter is generally used. It is desirable that both the ammeter and the voltmeter have the same period and that this be short. In the appendix are shown wiring diagrams for a potentiometer-voltmeter and a vacuum-tube voltmeter. The cost of the parts for these meters is not large but considerable time and labor are required for their assembly. For this reason purchase rather than construction of the meters is recommended if a manufacturer can be found.

2. **Reference electrodes.** A copper-copper sulphate electrode[13] is com-

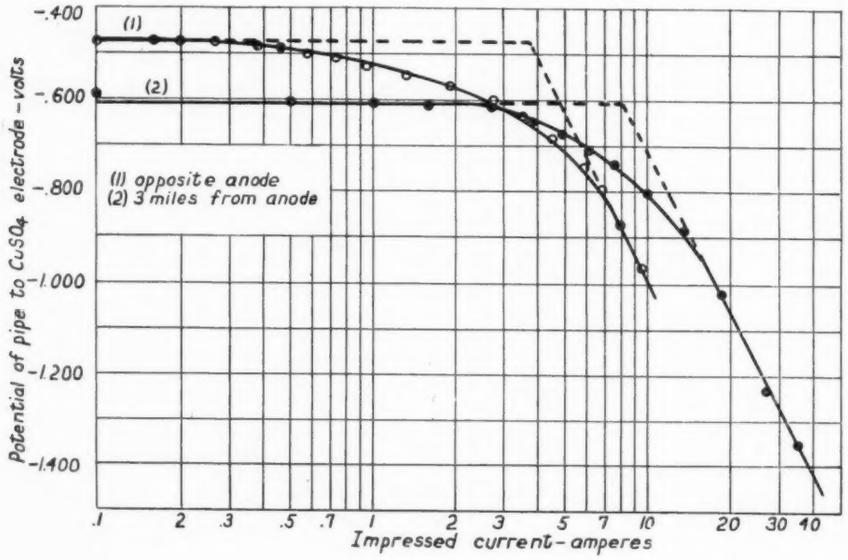

Fig. 5. Current-potential curves for 6-in. pipe

monly used as a reference electrode for field tests. Its essential features are an insulating container with a porous plug in one end filled with a saturated copper sulphate solution in contact with a rod or strip of copper. When the electrode is carefully constructed, with proper treatment the potential of this electrode will remain constant within a few millivolts. The resistance of the usual sizes is high — that of the electrode 8 in. long and ¾ in. in diameter supplied with the earth current meter being about 100 ohms. This does not include the resistance of the soil in which the electrode is placed. In one test the resistance between two such electrodes placed 2 ft. apart in moist soil was about 1100 ohms. When electrodes 2 in. in diameter were substituted the resistance between them dropped to 760 ohms. The resistance of one of these electrodes was about 64 ohms. Hence, the size of the electrode does not greatly affect the resistance of the meter that must be used with it. However, the area of the copper in the electrode and the form of the electrode affect the amount of current which can flow through it without making the electrode unstable because of polarization. Ewing[14] has made an extensive study of the copper sulphate electrode and has described an improved form suitable for accurate field work. Polarization changes the potential of the Ewing electrode 1 mv. when the current density is 0.125 milliampere per sq. cm., whereas the same form of electrode with the bright copper is changed the same amount by one-tenth of that current density. Ewing's investigation does not indicate the critical current for long tubular electrodes as the current density over the copper in such electrodes is not uniform.

Because of its construction the Ewing electrode must be carried in an upright position with little shaking. Violent shock should be avoided as the electrode is made of porcelain and glass. It is essential that the porous end of any copper sulphate electrode be kept moist. Recently the writer found that he could accomplish this by putting the end of the electrode in a tight-fitting rubber tube, one end of which was closed by a rubber stopper. Old-style electrodes so equipped can be filled with liquid and shipped in any position without leakage. They remain in good condition indefinitely. Of course the rubber cap must be removed before the electrode is used.

An objectionable feature of the copper sulphate electrode is the high difference of potential between it and steel. This requires the use of a voltmeter having a range of 1 volt or more, and small changes in the potential differences are determined with difficulty. To overcome this difficulty by the use of a more sensitive meter the author recently experimented with an electrode consisting of a one-inch insulating tube closed at one end by a wooden disk. The tube was filled with a saturated solution of cadmium sulphate in which was placed a ½-in. cadmium rod held in place by a rubber stopper. A binding post was attached to the rod. This is a crude modification of Ewing's cadmium sulphate electrode.[15] The difference of potential between this electrode and steel was quite low and reversed in direction in different electrolytes because of changes in the potential of steel with changes in pH value of the electrolyte. As this necessitated the use of a zero-center voltmeter and a reversible backout circuit, the development of the electrode was abandoned. Such an electrode, however, might be useful in regions where the pH values of all the soils rendered the steel either positive or negative with respect to the electrode.

A steel electrode that has certain advantages has been described by Rhodes.[16] A cone-shaped piece of pipe steel tipped with an insulating button is attached to an insulated rod. Such a rod can be placed in a hole within a definite short distance from the surface of the pipe and thus the IR drop through the earth can be reduced. The potential of this electrode may be affected by an abnormal condition at the point where the electrode is placed. Moreover, the potential of the steel depends on the pH value of the electrolyte.[3] This electrode is not as constant in potential as a copper sulphate electrode but its low potential with respect to steel is an advantage, especially when the change in the potential of the pipe is the criterion for the protective current.

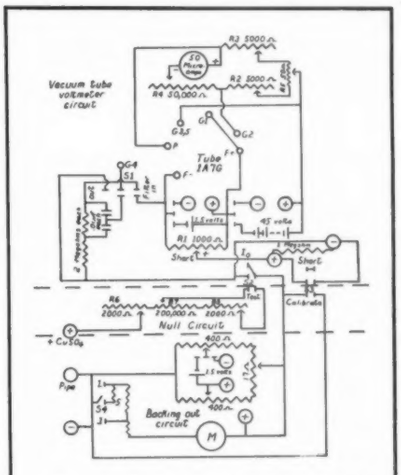

Fig. 8. Suggested null method circuit

The protective current is usually determined by connecting a variable source of power between the structure to be protected and a temporary or permanent anode and observing the current and potential required to bring the structure to a predetermined potential with respect to adjacent earth. Corrections for the resistance of the anode, and of any coating on the structure may or may not be made.

3. Apparatus for eliminating IR drop.

(a) By measurement and subtraction.

Ewing, in coöperation with Olson and McRaven of the United Gas Pipe Line Company, ran potential-log current curves by a method that involved measurement of the resistance between the electrode and a pipe line and the computation of the IR drop to be deducted from the observed potential. The results were only partly satisfactory, apparently because of errors in observations and in determining the IR drop. However, the results indicated that the current densities required for

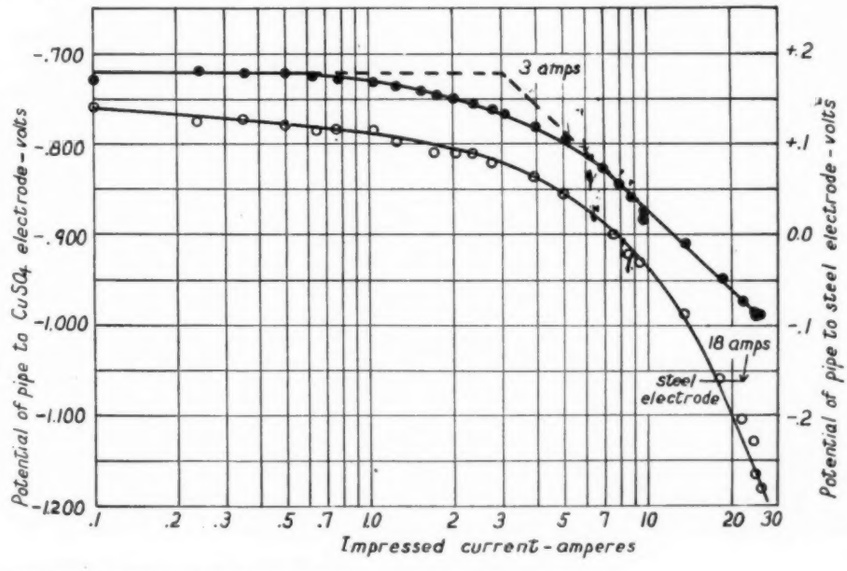

Fig. 7. Current-potential curves for 16-in. pipe

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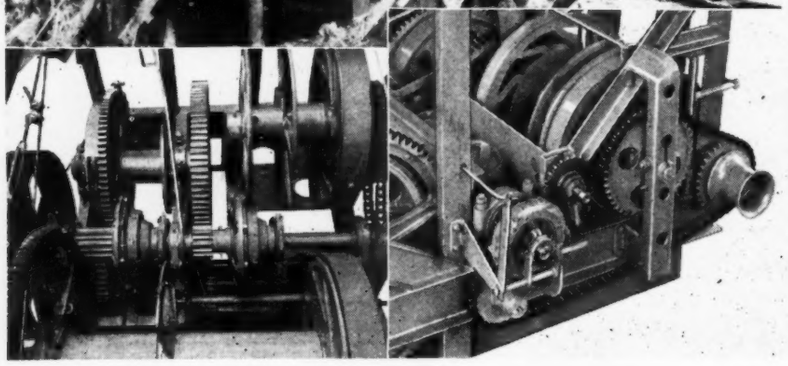

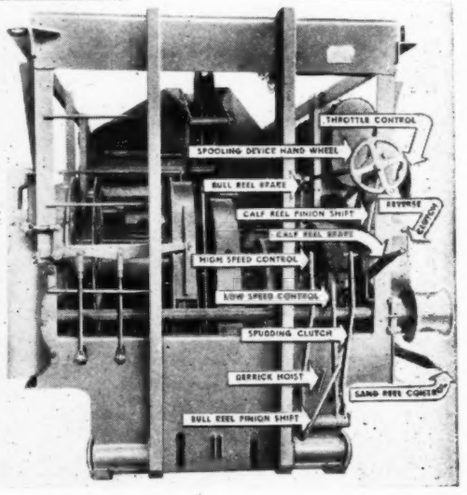

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protection, as well as the potentials of the pipes when protected, differed widely for different pipes and soil conditions. There appeared to be no relation between the current required for protection and the potential of the pipe when protected. These observations showed need for further investigation.

The next step in the use of current-potential curves for determining the protective current is presented not because of its intrinsic value but because with it good results can be obtained with instruments and apparatus found in many laboratories. This is of considerable importance when priority regulations and financial considerations prevent the construction of the preferable apparatus to be described later.

The origin of the circuit in Fig. 1 is not known to the writer. It was proposed to Denison by Hadley and has been used successfully by these men and by the writer. In Fig. 1, R_2 and R_3 each consists of a high and a low resistance rheostat with sliding contacts. (A single variable resistor would serve.) Across the ends of the resistors batteries are connected, while voltmeters E and $\triangle E$ are connected across the sliding contacts. The voltmeters are also connected in series with a galvanometer G, a high variable resistor R_4 that protects the galvanometer and prevents the polarization of the electrode, a copper sulphate electrode and the structure to be protected. The deflection of the galvanometer caused by the flow of current between the copper sulphate electrode and the pipe may be reduced to zero by adjusting the positions of the sliding contacts. When the galvanometer shows no deflection with R_4 cut out, the sum of the voltage shown by the voltmeters is the potential of the electrode with respect to the pipe and is independent of the resistance of the instruments used but includes an IR drop between the electrode and the structure.

The operation of the circuit is as follows: A rheostat, ammeter, switch, and a source of current such as a group of storage batteries or a single battery and a generator are so connected between the structure and a temporary or permanent anode that the current may be changed by about 10 percent by means of the switch, which should not open the circuit. Computations are simplified if the change is exactly 10 percent, which can be accomplished by using 11 cells having the same voltage.* The original potential is first obtained with no current flowing and with $\triangle E$ reading zero, by opposing or backing out the potential across the galvanometer until it is reduced to zero by means of the potentiometer resistor R_2, while R_4 is gradually cut out. When the galvanometer deflection is reduced to zero the voltmeter across the potentiometer shows the potential of the structure with respect to the electrode. A small current is then applied between the anode and cathode and the potential between the electrode and the structure reduced to zero by means of R_2 as before. Next the current is increased by 10 percent by means of the switch and the resulting deflection of the galvanometer reduced to zero by means of the potentiometer R_3. The change in voltage $\triangle E$ will be due to the change in $\triangle I$ and the IR drop involved in the reading, E, is $I \times \frac{\triangle E}{\triangle I}$, or if $\triangle I$ is O.1I, $IR = 10\ \triangle E$. The true potential of the pipe is therefore $E - IR$ or $E - 10\ \triangle E$. This value is plotted against the logarithm of the current. The initial current is then increased by 25 or 50 percent, and new values for I, E, and $\triangle E$ obtained. At first there will be little or no change in the value of $E - \triangle E$. As the current is increased a point will be reached beyond which a noticeable change in $E - \triangle E$ is observed. The test is continued until four or five definite changes have been obtained or until the data show that the structure is acting as an over-voltage electrode. When the current is increased sufficiently two changes take place at the cathode—a rapid one due to the polarization of the cathode and a slow one, caused by the accumulation of alkali. The best curves will be obtained if the observations of E are made at equal time intervals so chosen that the change in polarization is nearly complete and the change in alkali concentrations is small. Intervals of from one to five minutes are usually satisfactory.

*The change in current will be proportional to the change in the number of cells only if all cells are alike in voltage and resistance and the resistance of the battery is low when compared with the resistance of the external circuit.

Consideration of the procedure just outlined will make it clear that any error in the determination of $\triangle E$ or $\triangle I$ is multiplied by 10. This error is reduced by (a) making $\triangle I = 0\text{-}1I$ or some other known percent of I as this makes the reading of $I + \triangle I$ unnecessary, (b) using a resistor that can be adjusted exactly, and (c) using a low reading voltmeter to measure $\triangle E$.

(b) By the null method.

The difficulties encountered by Ewing and McRaven led the latter to suggest a two-electrode circuit for eliminating the IR drop, and this was the forerunner of the null circuit developed by Pearson for laboratory research on electrode phenomena and modified by Hadley for field use. Fig. 3 shows the essential features of the Pearson-Hadley null circuit. Drawings from which the apparatus may be constructed are given in the appendix. It will be noted that when the switch S_2 is closed downward the circuit is the same as that of Fig. 1 except that the potentiometer and meter for obtaining $\triangle E$ have been eliminated and a vacuum tube voltmeter V has been substituted for the galvanometer and its series resistance. The operation of the circuit is as follows. With the current circuit open and S_2 in the down position, the null circuit is opened and the original potential of the structure is obtained as

Fig. 9. Top of instrument

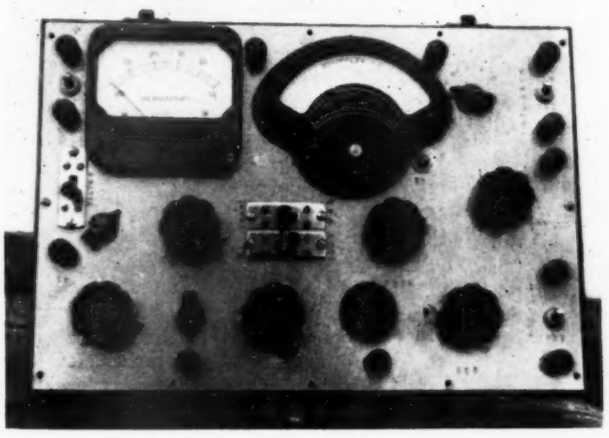
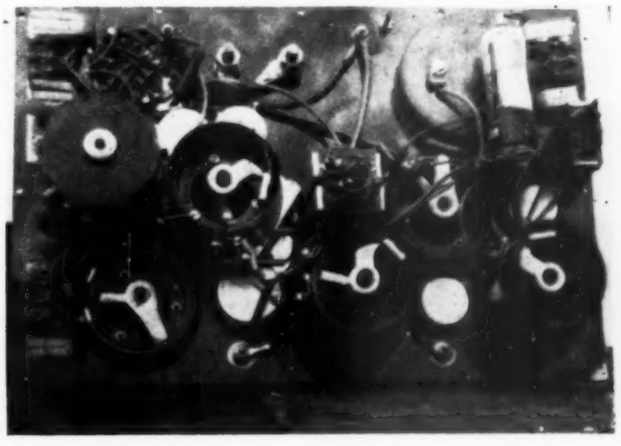


Fig. 10. Interior of instrument



by the earlier method. S_2 is then reversed, the current circuit closed, and the rheostat, R_1, is adjusted to permit the passage of the estimated protective current or of any other current sufficient to cause a well-defined change in the reading of the vacuum-tube voltmeter when S_1 is shifted. The switch S_1 is then moved from side to side, and the sliding contact N on the null potentiometer is adjusted until changing the position of the switch S_1 causes little or no change in the reading of the vacuum-tube voltmeter, which is serving as a null galvanometer. When a change in I does not affect the deflection of the galvanometer the latter is obviously not affected by an IR drop in its circuit.

A comparison of the null circuit in Fig. 3 with the Wheatstone bridge circuits below it in which corresponding points have been similarly lettered may make the operation of the circuit clearer. The batteries in the lower right bridge circuit represent the voltage supplied by the potentiometer and the potential of the pipe with respect to the reference electrode. If the bridge has first been balanced with respect to resistances (IR drops) the galvanometer, V, will read zero when the voltage supplied by the potentiometer equals the potential of the pipe.

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After the bridge or null circuit has been balanced for a current to which it is sensitive, the current is reduced to a very small value. When sufficient time has elapsed for the vacuum-tube voltmeter V to reach a steady state, the potential across it is reduced to zero by means of the potentiometer resistor R_2 and the readings of the ammeter I and the voltmeter M are recorded. The rheostat R_1 is then readjusted to pass from 30 to 50 percent more current and a new balance is obtained. Thus a series of observations of E and I are accumulated. At first little or no change in E will result from a change in I. Later noticeable change will be observed. Observations should be continued until four or more definite changes in E have been obtained.

Usually it will not be necessary to readjust the null circuit until after the critical current has been passed. In some cases the circuit becomes badly unbalanced for large currents. It is advisable to check the balance of the null circuit from time to time. The data for the broken line in Fig. 2 were obtained by means of the Pearson-Hadley circuit on the same structure that supplied the data for the solid curve six months earlier. The later data are obviously much better than the first set. The small difference in the values of the critical currents shown by the two curves may be attributed to differences in soil conditions or to the fact that current had been applied intermittently to the structure for about a week prior to the running of the second curve. Fig. 4 shows a potential-current curve obtained by Hadley on 40 ft. of a 16-in. bare steel pipe using a null circuit.

The curves so far presented were obtained at points quite close to the place where the wire from the generator was attached to the pipe and where the anode was quite near the pipe. Fig. 5 presents data obtained by Hadley at a certain point on a welded 6-in. pipe line. The apparatus used in obtaining the data for curve (1) was set up near the point where the power was connected to the pipe as in previous tests, but the anode was about a quarter of a mile from the pipe and the nearest copper sulphate electrode to it was about 125 ft. from the pipe.

The voltage data for curve (2) are for a point on the same pipe about three miles from the power connection. The welding generator, ammeter and control rheostat were at the same place in each test. In the second test communication was by radio, but a modification of Smith's communication system described in Ewing's book[4] under the topic "Measurement of Network Constants" might have been used. One copper sulphate electrode was placed over the pipe and the other electrode

was about 90 ft. from the pipe. Curve (2) in Fig. 5 is presented to show that the null method can be used to obtain data at points remote from the power connection.

Comparison of Results

As the apparatus required for the Pearson-Hadley method for determining the current required for the protection of a buried structure is obviously more complicated than that in common use, and as the time required for the newer test is longer, it is of interest to consider whether the different methods give similar and equally valid results.

Fig. 6 shows current-potential curves taken in several ways. The cathode was a buried steel tank with 8-in. by 12-in. steel plates placed about 8 in. from the tank near the top, middle, and bottom, and separated from each other by about 10 ft. The side of the tank was coated with coal-tar enamel. The anode was about 300 ft. from the tank.

Curves 1, 2, and 3 show the potential of the tank with respect to the steel reference electrodes near the top, center, and bottom of the tank. It will be noted that the tank is at nearly the same potential with respect to the top and bottom electrodes and that there is a difference of potential of nearly 0.3 volt between the top and middle electrodes.

If the tank is protected when its potential is 0.3 volt more negative than that of the reference electrode, 1.3 amp. is required for protection according to the indication of the central electrode, while the static potentials of the other electrodes indicate that no current is required. If a change in potential of 0.3 volt with respect to a steel electrode is the criterion, the required currents are 1.4 amp., 1.5 amp., and 1.9 amp., for the top, center, and bottom electrodes, respectively.

If a copper sulphate electrode is the reference point, curve (4) indicates that 0.32 amp. is the protective current on the basis of a potential difference of 0.85 volt and 1.3 amp. on the basis of a lowering of the potential by 0.3 volt. If the null method is used curve (6) indicates that a current of 0.7 amp. is required for protection.

Other curves obtained by the null method indicated that the protective current was 1.0, 1.1 and 1.2 amp.

For the tank under discussion it appears that the suggested change of 0.3 volt and the break in the curve by the null method give about the same results within the limits of reproducibility. Changing soil and electrode conditions make it impossible to determine a single value of current that will just provide protection at all times so far as the tank in question is concerned, and probably an engineer would have chosen about the same value for the protective current for this tank under consideration whatever his criterion.

Similar conclusions do not always result from such comparisons of methods. Fig. 7 shows the results of two tests run simultaneously by Hadley and others on a 40-ft. section of bare steel pipe that was separated from the remainder of the line by a Dresser coupling. The upper curve was obtained by the null method. It indicates that 3 amp. are required to protect the section. A similar test run a few hours earlier indicated 2.5 amp. were required for protection. The lower curve was obtained by the usual method, using a potentiometer voltmeter and a steel electrode placed ⅛ in. above the pipe and a foot to one side of the copper sulphate electrode used for the null method. This curve also changes in direction at about 3 amp. It indicates that 18 amp. are required to lower the potential of the pipe by 0.3 volt. A third simultaneous test employing another steel electrode 1 ft. on the other side of the $CuSO_4$ electrode indicated that 30 amp. were required for protection. A protective system installed by a consulting engineer was supplying 0.1 amp. for the protection of this section.

Incidentally, the data for Figs. 4 and

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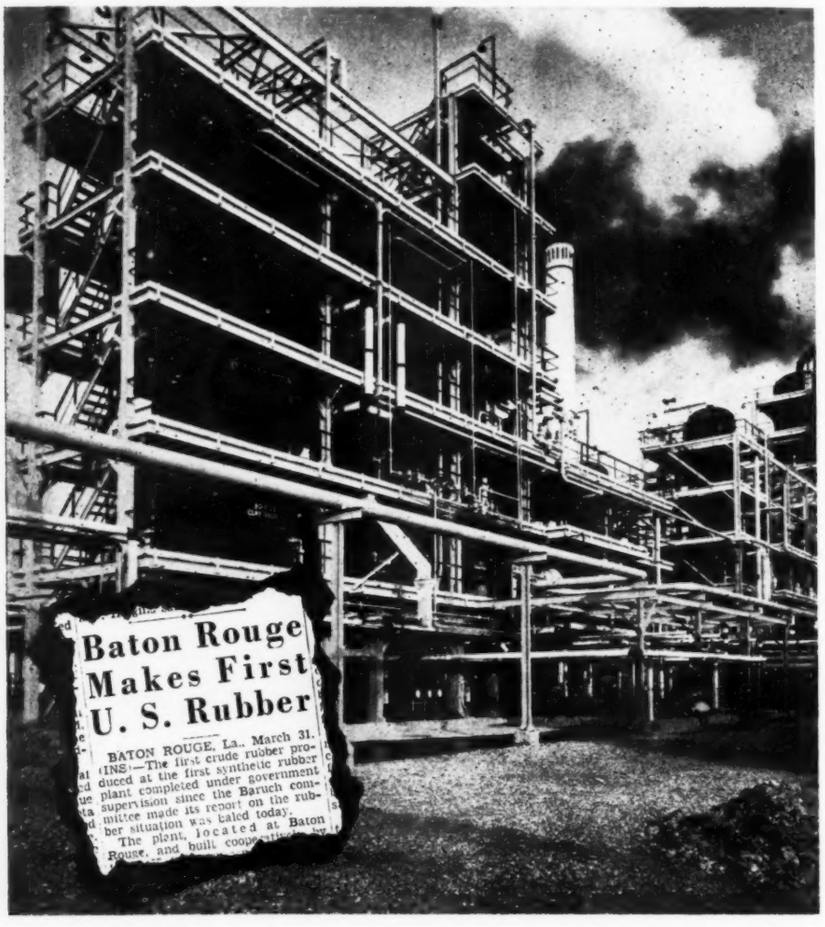
7 were taken with the same set-up at points 11 miles apart on the same pipe. It will be noted that both the open-circuit potentials and the currents required for protection are quite different. The current actually being applied for the protection of the section in Fig. 4 is 40 percent greater than that applied to the section in Fig. 7.

Conclusions

It has been shown that neither the potential of the pipe with respect to a reference electrode nor a change in this potential is a reliable criterion of the condition of a pipe with respect to corrosion. A method for determining when a pipe is protected by means of an applied current has been developed from both theory and experiment. This method is more reliable than the ones in common use but it requires more apparatus, more test current, and more time. The method has been used successfully under a variety of conditions but there may be conditions such as the presence of large fluctuating stray currents or conditions requiring large amounts of power where the application of the new method is impractical. The use of the newer method may result in a saving of current but the chief reason for its use is the greater reliability of the results obtained in this way.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Acknowledgment

This report is chiefly an account of the work of others. The original draft of the report has been read by Pearson, Hadley, Smith, and Denison, whose suggestions have been considered but not always followed. They should not be held responsible for any incorrect statements of fact or theory but thanks are due them, and others whose work has been cited, for the development of a better means of determining when cathodic protection has been attained.

Appendix

(The design and use of apparatus for applying the null method of determining the current required to prevent corrosion of a buried structure.)

1. Design of apparatus. The following description of apparatus assembled and successfully used by the writer in the application of cathodic protection is presented for the information of those desiring to construct such apparatus.

The upper part of Fig. 8 is essentially the circuit proposed by Garman and Droz[17] with the addition of a filter and some variable resistances. The microammeter used was a Model 801 Weston meter with a resistance of about 900 ohms. Other makers can supply equally suitable meters. One with a range of 10 or 20 microamperes would be preferable. The essential features of the meter are high sensitivity, high resistance, short period, critical damping, and a large scale. As it is used as a null instrument high accuracy is not essential.

The zero position of the meter is adjusted by R_1. It is affected by R_2 and R_3, and by R_4 also if the relative values of R_2 and R_3 are not properly chosen. The resistances R_2 and R_3 also affect the volt sensitivity of the meter as does the resistance R_4, which may be omitted if only the maximum sensitivity of the apparatus is desired. However, if R_4 is omitted some provision for protecting the microammeter while adjustments are being made should be provided. In the apparatus described R_4 is an 11-watt rheostat-potentiometer about 3 in. in diameter and 2⅝ in. high, exclusive of the stem and knob. A smaller and less expensive rheostat might save space and be as satisfactory. R_1 is similar to R_4. The other rheostats in the vacuum tube circuit are about 1½ in. in diameter and ½ in. thick. Small fixed resistances could be substituted if the resistances suitable for the tube to be used were predetermined. The zero position for the meter on open circuit is not the same as when the meter is connected across a resistance. Consequently, the terminals should be short circuited by means of switch S_3 before the zero position is adjusted. The megohm resistor across the terminals of

the meter reduces its instability, but it is unnecessary and probably of doubtful value. Mica condensers and 1-watt resistors were used in the filter, which may be cut into or out of the circuit by means of switch S_1. The vacuum tube voltmeter is on open circuit when S_1 is in the open or neutral position. The remainder of the apparatus may then be used with another vacuum tube meter or other high resistance meter connected across the positive and negative terminals associated with switch S_3.

Anderson and Hindman[18] have suggested a modification of the Garman and Droz circuit, which results in a more sensitive and flexible instrument. Pearson[19] has published the design of a vacuum tube voltmeter, which is more sensitive than the Garman and Droz meter and permits the use of an external meter, such as a Model 1 Weston voltmeter. The use of such a meter eliminates the need for a special instrument now secured with difficulty, but the Pearson circuit requires three large 90-volt B batteries and the instrument is therefore considerably heavier.

The portion of Fig. 8 between the broken lines is the Pearson null circuit modified by the addition of two rheostats, R_6 and R_9, on a single shaft and so connected that the resistance in one is decreased as that of the other is increased. The three potentiometer-rheostats R_6, R_7, and R_8 are similar to the large ones in the vacuum tube circuit although small ones might be used. Switch S_2 enables the operator to cut out the null circuit and connect the vacuum tube meter directly to the backing-out circuit, shown in the lowest portion of Fig. 8. This is essentially a potentiometer-voltmeter circuit. The rheostat-potentiometers are so connected to a single shaft that the resistance of one increases as that of the other decreases. The 17-ohm rheostat-potentiometer provides a fine adjustment. The three rheostats used were each 3 in. in diameter and 1¼ in. high, but a single small rheostat might be substituted at a sacrifice of ease and precision of adjustment. A voltmeter having a resistance of about 60 ohms per volt was used because it was available. A voltmeter having a much higher resistance would be preferable because it would permit the use of rheostats having higher resistances and this would reduce the drain on the battery.

With switch S_3 in the position marked "Calibrate" the vacuum tube voltmeter is in parallel with the voltmeter M. This permits the calibration of the vacuum tube voltmeter. Such calibration is necessary if the vacuum tube voltmeter is used to measure potentials. An external meter may be substituted for the meter M if switch S_4 is

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opened. Provision has been made in the diagram (Fig. 8) for the use of each of the three circuits separately and for the substitution of external batteries and meters in case trouble develops or measurements beyond the range of the apparatus are to be made. The apparatus contains a 45-volt B battery weighing about 1½ lb. and two 1.5-volt batteries each weighing about 1 lb. The catalog prices of the instruments, rheostats, switches, etc., total about $90. The apparatus is enclosed in a metal box with a removable cover and a folding handle on one end. The box is 15 in. long, 10 in. wide, and 6 in. deep. The weight of the apparatus is 23 lb. At the sacrifice of some ease of adjustment, flexibility, and reliability, the size, weight, and cost of materials could probably be reduced 50 percent. It should be noted that the estimates of cost do not include labor, which in laboratory-made apparatus usually amounts to much more than the cost of materials if the salary of the technician is considered. Figs. 9 and 10 show the outside and the inside of the apparatus.

2. **Use of apparatus.** The steps to be taken to obtain potential-current curves for determining the current required for cathodic protection have been described. However, some details regarding the manipulation of the apparatus may be helpful to those just beginning to use it. One copper sulphate electrode is usually placed over the pipe. This electrode is connected to the positive side of the vacuum tube voltmeter. The other reference electrode, connected to the binding post marked $+Cu\,SO_4$, is placed from 20 to 100 ft. from the pipe, preferably in such a position that the IR drop in the earth between the pipe and the nearer electrode is approximately equal to that between the two electrodes. The accuracy of the adjustment of the backing-out circuit can be improved by adjusting it until short-circuiting the vacuum tube voltmeter causes no kick or deflection of that meter. This has proved much better than an attempt to reduce the deflection of the vacuum tube voltmeter to a predetermined zero, partly because there is often a slight drift of the zero position.

Increasing the polarizing current in steps of from 30 to 50 percent results in a curve with points of observation well spaced on semi-log coördinate paper.

It is important that observations be taken at approximately equal-time intervals. Three to five minutes have been found suitable and sufficiently long to permit quick checks of the null adjustment. The steps required for a current-potential curve are as follows:

1. With no current imposed on the structure to be protected determine the potential of the structure with respect to the nearby electrode (S_2 in the I_0 position, S_3 open).

2. With current flowing between anode and cathode adjust null circuit until a change of 10 percent in the applied current causes no change in the deflection of the vacuum tube voltmeter (S_2 in the Test position, S_3 open). The pointer of the vacuum tube voltmeter may be kept on the scale by adjustment of the backing-out circuit.

3. Reduce the applied current to a very low value and bring the vacuum tube voltmeter to zero by means of the backing-out circuit. The reading of the meter M is then the true potential of the structure with respect to the nearby electrode.

4. Increase applied current in steps of 30 percent and note corresponding values of current and potential.

5. Plot the relation of the potential to the current on semi-log paper as in Fig. 4 or the relation of the potential to the logarithm of the current with the latter as the independent variable. The early observations should lie on a nearly horizontal line, which will merge into a curve followed by a sloping straight line if the balance of the null circuit is maintained. The intersection of projections of the two straight lines is the current required to protect the section of the structure under observation under the conditions existing at the time of the test.

As alkali accumulates at the cathode the current required for protection usually is reduced. Polarization caused by accumulation of hydrogen persists for some time after the protective current is reduced. For these reasons if the steps outlined above are repeated in reverse order the curve obtained will fall below the original curve. The break in the curve will be at about the same current, but the horizontal part of the curve will usually be below the original line, i.e., the structure will be temporarily more negative with respect to the reference electrode when the protective current is cut off. If excessive values of the protective current are applied a second break in the curve may be obtained. This has been attributed to reduction of the oxide film originally on the structure. High protective currents may also cause an unbalancing of the null circuit, possibly because of a change in the resistance of the soil adjacent to the cathode.

The first curves obtained by an operator will probably be irregular and unsatisfactory, but very satisfactory curves are usually obtained after the operator has become familiar with the apparatus and methods of test. A great deal more work must be done before the method can be easily applied under all conditions and before all the phenomena related to the method are fully understood. However, practicability and usefulness of the method under a fairly wide range of conditions have been demonstrated, and it is highly probable that the ingenious engineer will find ways to adapt the method to whatever problem of cathodic protection is presented to him.

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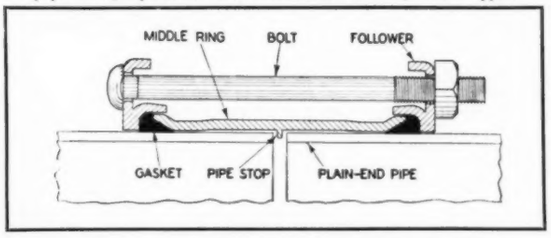

Above: Section view of Style 38 Regular Dresser Coupling

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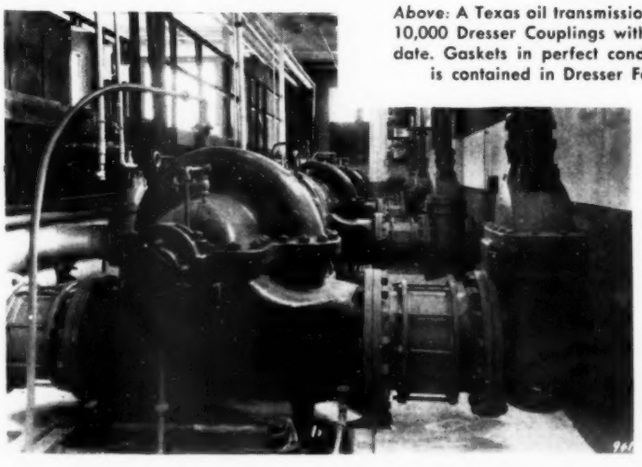

Above: Dresser Style 38 Regular takes care of slight misalignment in making this permanent refinery pump installation at Augusta, Kansas, and absorb vibration without leakage. Equipped with Armored gaskets, "Dressers" may be used on lines carrying gasoline, kerosene, naphtha, lubricating oil and other petroleum products

Above: Here Dresser Style 40 Long Couplings simplify work at five connections, spanning the gap where pipe ends do not meet

P 615.635.4

Current Density Related to Current Distribution*

By HARRY GEAR
Lone Star Gas Company

Introduction

IT HAS been assumed by the writer that a measurement of current density is a criterion by which the degree of corrosion mitigation can be determined. This report presents a method of correlating potential measurements (IR drop) on consecutive uniform intervals of bare pipe line with the total current drained and the distance from the point of drainage. The relation of current distribution to current density is expressed by the empirical relation derived from an analysis of the line current flowing under a condition of forced drainage. This method of analysis introduces a rational solution of the current requirements.

Test Procedure

The pipe line to be investigated must be exposed to a system of forced electrical drainage so that the distribution of a known amount of current can be determined. The pipe line is explored by the usual method of measuring IR drops along consecutive uniform intervals.[1] In making this investigation any convenient contact interval that is suitable to the range of the voltmeter or potentiometer available may be chosen. Beginning at the negative return consecutive IR drops are measured in each direction along the line until the section under investigation has been covered.

The observed readings are then plotted on semilog coördinate graph paper. IR drops measured in millivolts are plotted on the logarithmic ordinates corresponding with the distance measured in feet to the mid-point of the contact interval.

Interpretation of Data

If reference is made to the various graphs included herein, it will be noted that the plotting of these data indicates straight line distribution; except in situations where (a) the conductivity of the soil is not uniform, and (b) where the forced drainage current is so small that it will be materially affected by the normal soil or long line currents.

In situations where the conductivity of the soil changes this circumstance will be reflected by a change in the slope of the current distribution curve irrespective of the initial current drained and of the distance from the drain. (Fig. 5.)

In situations where the magnitude of the current imposed under forced drainage is materially affected by the influence of earth or long line current this circumstance will likewise be reflected by a departure from straight line distribution. (Figs. 1 and 2.)

The extent of this condition, however, is dependent upon the current density existing at a given location, which, in turn, is a function of the initial magnitude of the current drainage and the distance from the drainage point.

Obviously the situation discussed under item (b) will have a universal application and the divergence from the straight line distribution arising from this particular cause merely indicates the limit of effective current application.

From the relationship shown by the

*Presented before National Bureau of Standards' Soil Corrosion Conference, St. Louis, Missouri, March 25-27, 1943.

Fig. 1

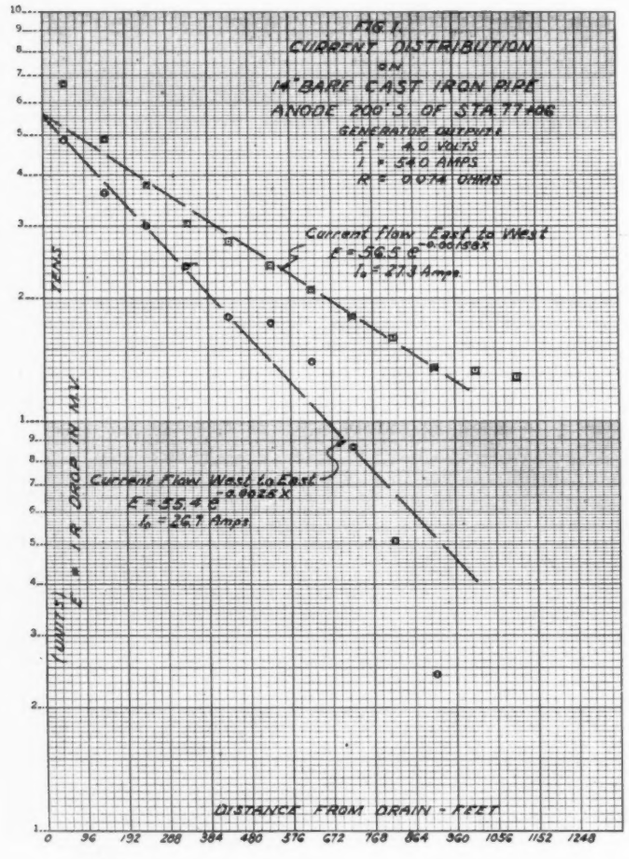
FIG 1
CURRENT DISTRIBUTION
ON
14" BARE CAST IRON PIPE
ANODE 200' S. OF STA 77+06
GENERATOR OUTPUT
E = 4.0 VOLTS
I = 540 AMPS
R = 0.074 OHMS
Current Flow East to West
E = 56.4 e^-0.00198X
Io = 27.3 Amps
Current Flow West to East
E = 55.4 e^-0.0028X
Io = 26.7 Amps
E = I R DROP IN M.V.
(VOLTS)
DISTANCE FROM DRAIN - FEET
0 96 192 288 384 480 576 672 768 864 960 1056 1152 1248

Fig. 2

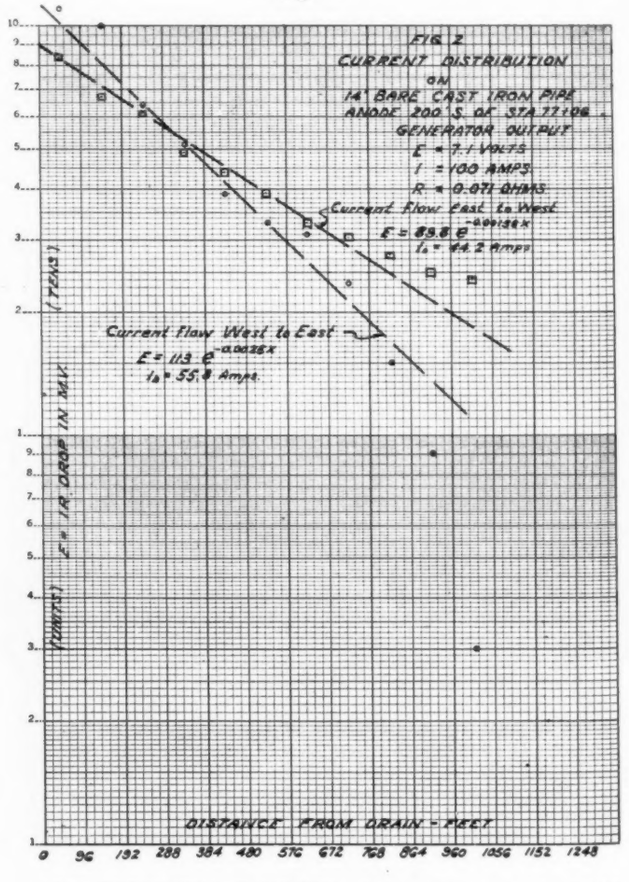
FIG 2
CURRENT DISTRIBUTION
ON
14" BARE CAST IRON PIPE
ANODE 200' S. OF STA 77+06
GENERATOR OUTPUT
E = 7.1 VOLTS
I = 100 AMPS
R = 0.071 OHMS
Current Flow East to West
E = 89.8 e^-0.00136X
Io = 44.2 Amps
Current Flow West to East
E = 119 e^-0.0028X
Io = 55.8 Amps
E = I R DROP IN M.V.
(VOLTS)
DISTANCE FROM DRAIN - FEET
0 96 192 288 384 480 576 672 768 864 960 1056 1152 1248

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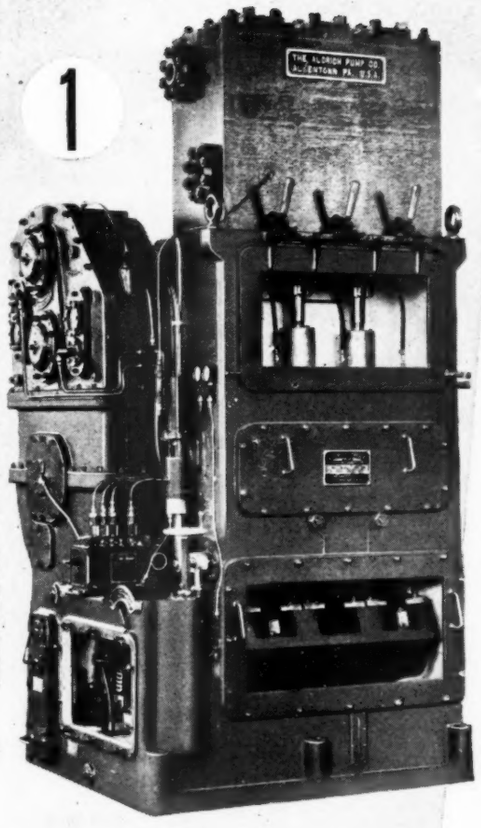

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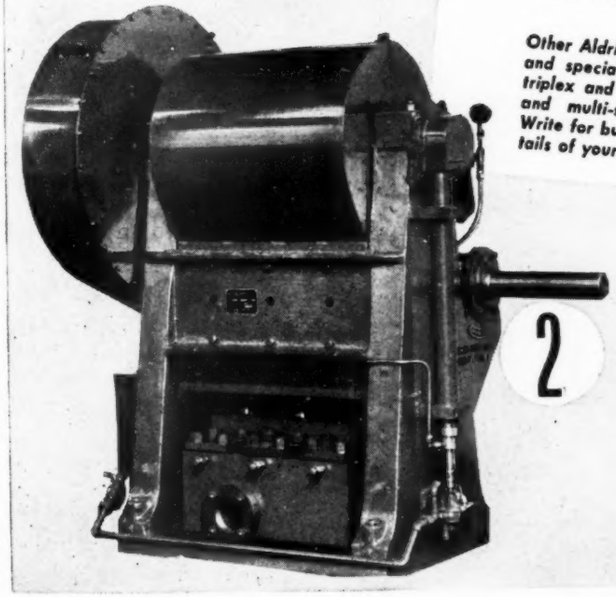

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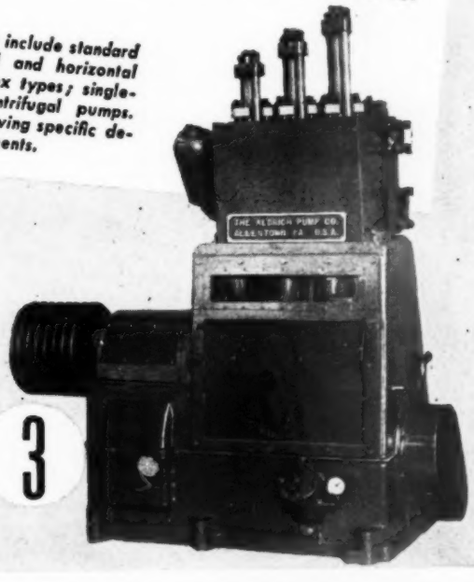

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graphic analysis of these data, the following empirical relationship is indicated:

$$E = C e^{-mx} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

Where:

E = IR drop in mv.,

C = constant, expressed in mv. This constant is a function of the unit resistance of the pipe line, the length of the contact interval and the magnitude of the current drained,

e = 2.718,

X = distance from the point of drainage to the mid-point of the contact interval,

m = slope of the curve plotted to logarithmic coördinates. This factor is a function of the soil resistivity and the resistance of the anodic and cathodic surfaces.

From Ohm's Law the following relation exists:

$$1000\ IR = Ce^{-mx}$$

Transposing:

$$I = \frac{C}{1000R} e^{-mx} \quad . \quad . \quad . \quad . \quad . \quad (2)$$

Where R is the resistance of the section of pipe between the points of contact. A further refinement of equation (2) is made by rationalizing the factor $\frac{C}{1000R}$.

If the distance from the drainage point to the mid-point of the contact interval is zero feet, then:

$$I = \frac{C}{1000R} = I_d \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

and $\frac{C}{1000R}$ can be replaced by the drainage current, I_d

Whence:

$$I = I_d e^{-mx} \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

The current collected by the line between the points x_1 and x_2 is expressed as follows:

$$\sum_{x_1}^{x_2} I = I_d (e^{-mx_1} - e^{-mx_2}) \quad . \quad (5)$$

or

$$\sum_{x_1}^{x_2} I = \int_{x_1}^{x_2} dI \quad . \quad . \quad . \quad . \quad (6)$$

Differentiating equation (4):

$$dI = -mI_d e^{-mx} dx \quad . \quad . \quad . \quad . \quad (7)$$

The current density is the current collected per unit area:

$$\Phi = \frac{dI}{dA} \frac{dI}{\pi D dx} \quad . \quad . \quad . \quad . \quad (8)$$

where D is the diameter of the pipe in feet. Dividing equation (7) by dA we have:

$$\Phi = \frac{mId\, e^{-mx}}{\pi D} \quad . \quad . \quad . \quad . \quad (9)$$

When Φ is the current density expressed in amp. per sq. ft. caused by the drainage current I_d at any point x ft. from the negative return. As the current density considered necessary for protection is measured in milliamperes per sq. ft., equation (9) is converted to this basis and becomes:

$$\Phi = \frac{1000mI_d e^{-mx}}{\pi D} \quad . \quad . \quad (10)$$

Referring to equations (3) and (4) when the drainage current is to be determined in a single direction, the I_d value for any one direction is determined by prorating the total output on the basis of the intercept values; or it may be calculated from a known or calibrated resistance value of the length of line in the contact interval direct from the IR drop measured on each section adjacent to the drain.

Sample Calculation

Fig. 7 illustrates the results of an exposure test on a 10,000-ft. section of bare welded steel pipe. The negative return was located at Station 62 plus 50 and the total current drained was 40 amp.

Based upon intercept values, the pro rata portion of current flowing each side of the negative return are 20.2 amp. flowing from east to west and 19.8 amp. west to east.

Using the point slope method, the slope is calculated as follows:

Fig. 3

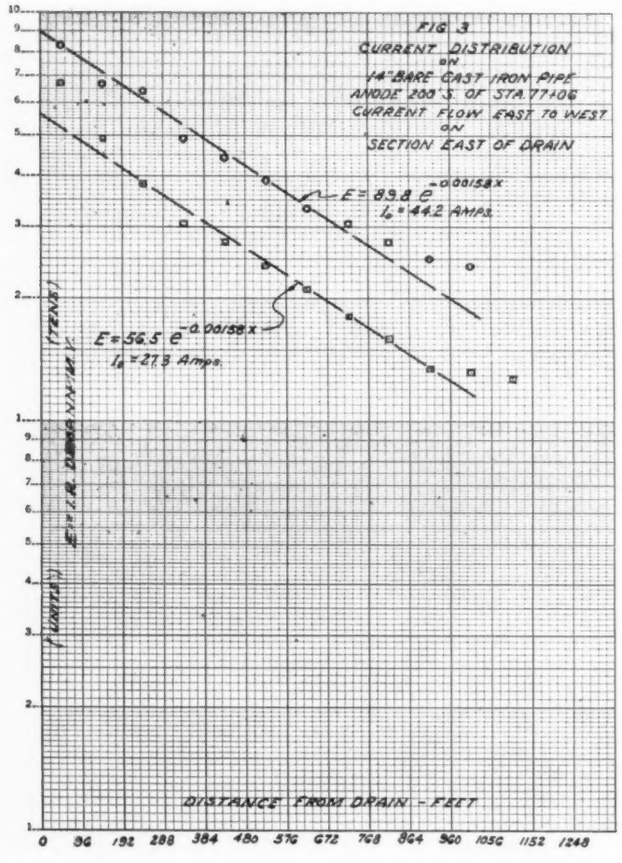


FIG 3
CURRENT DISTRIBUTION
ON
14" BARE CAST IRON PIPE
ANODE 200' S. OF STA. 77+06
CURRENT FLOW EAST TO WEST
ON
SECTION EAST OF DRAIN
E = 89.8 e^-0.00158x
I_d = 44.2 AMPS.
E = 56.5 e^-0.00158x
I_d = 27.8 Amps.
E = IR DROP IN MV. (LOGARITHMIC)
DISTANCE FROM DRAIN - FEET
0 96 192 288 384 480 576 672 768 864 960 1056 1152 1248

Fig. 4

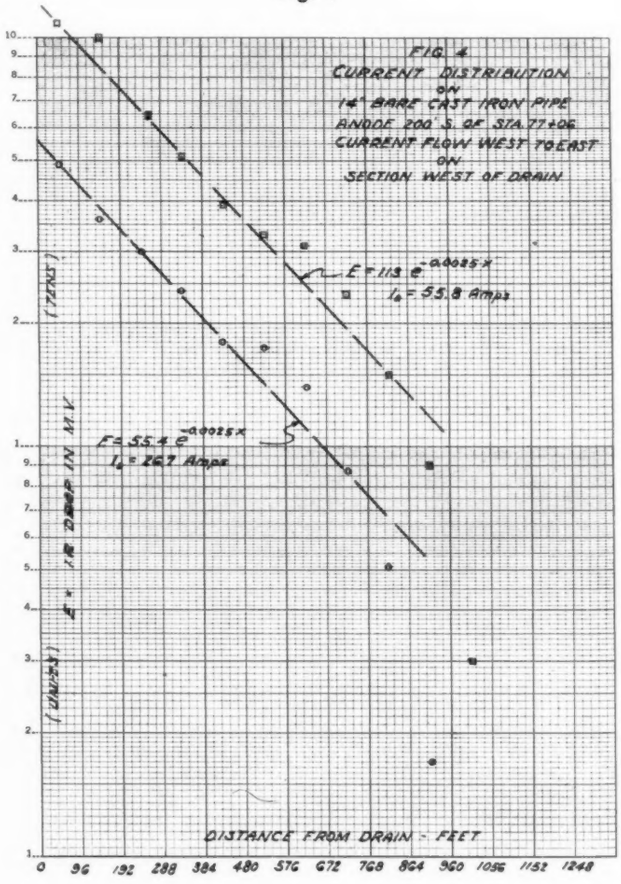


FIG 4
CURRENT DISTRIBUTION
ON
14" BARE CAST IRON PIPE
ANODE 200' S. OF STA. 77+06
CURRENT FLOW WEST TO EAST
ON
SECTION WEST OF DRAIN
E = 113 e^-0.0025x
I_d = 55.8 Amps
E = 55.4 e^-0.0025x
I_d = 26.7 Amps
E = IR DROP IN MV. (LOGARITHMIC)
DISTANCE FROM DRAIN - FEET
0 96 192 288 384 480 576 672 768 864 960 1056 1152 1248

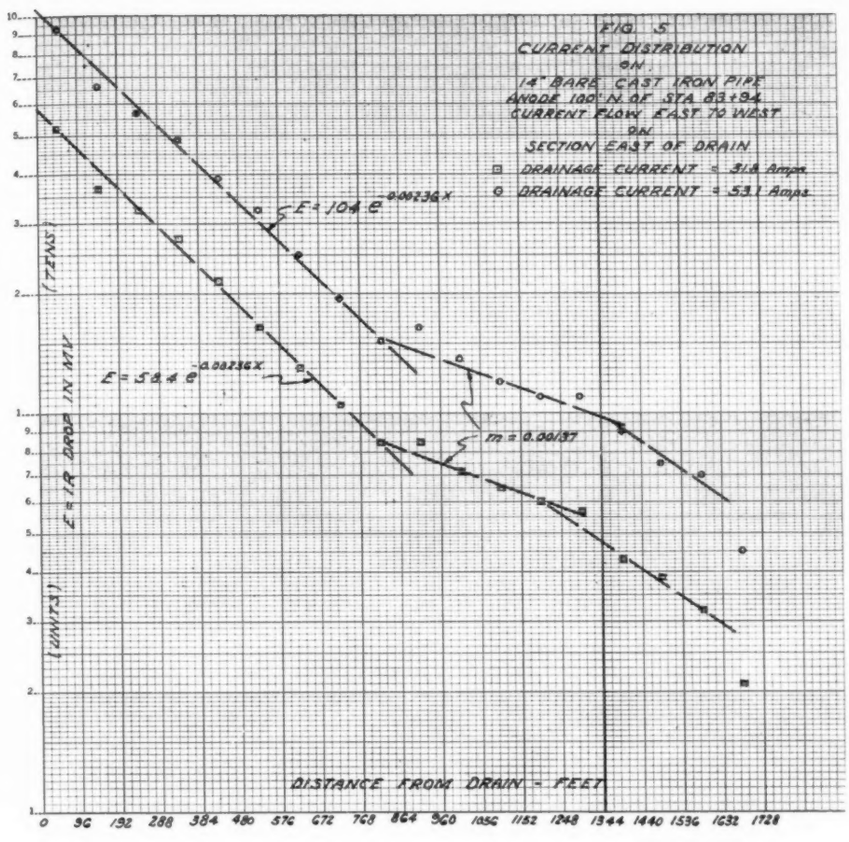


Fig. 5

$Y_1 = 47.0$ Log $Y_1 = 1.67210$ $X_1 = 0$

$Y_2 = 20.0$ Log $Y_2 = 1.30103$ $X_2 = 3500$

Log Y_1—Log $Y_2 = 0.37107$ $X_1 - X_2 = -3500$

$$m = \frac{0.37107}{-3500} = -0.000106$$

Converting to Log_e, $m = -0.000244$

$$I_x = 19.8e^{-0.000244}$$

Calculating the current flowing past Station 27 plus 50.

$-mx = -0.855$

$e^{-mx} = 0.425$

$I_x = 19.8 \times 0.425 = 8.41$ amp.

The current density over the section of pipe between Station 27 plus 50 and 62 plus 50 is calculated by substituting the above values in equation (10). The value of D, pipe diameter, is expressed in feet.

$$\Phi = \frac{0.244 \times 19.8\ e^{-0.000244x}}{3.1416 \times 1.16}$$

The value of Φ at Station 62 plus 50 where $X = O$ is

$\Phi = 1.32$ milliamperes per sq. ft.

The value of Φ at Station 27 plus 50 when $X = 3500$ ft. is

$-mx = -0.855$

$e^{-mx} = 0.425$

$\Phi = 1.32 \times 0.425 = 0.562$ milliamperes per sq. ft.

Each successive series of observed IR drops measured along the line exhibiting different slope characteristics must be treated individually. The recommended procedure is to consider that the drainage point of each section of different slope occurs at the point of maximum current value.

Discussion of Results

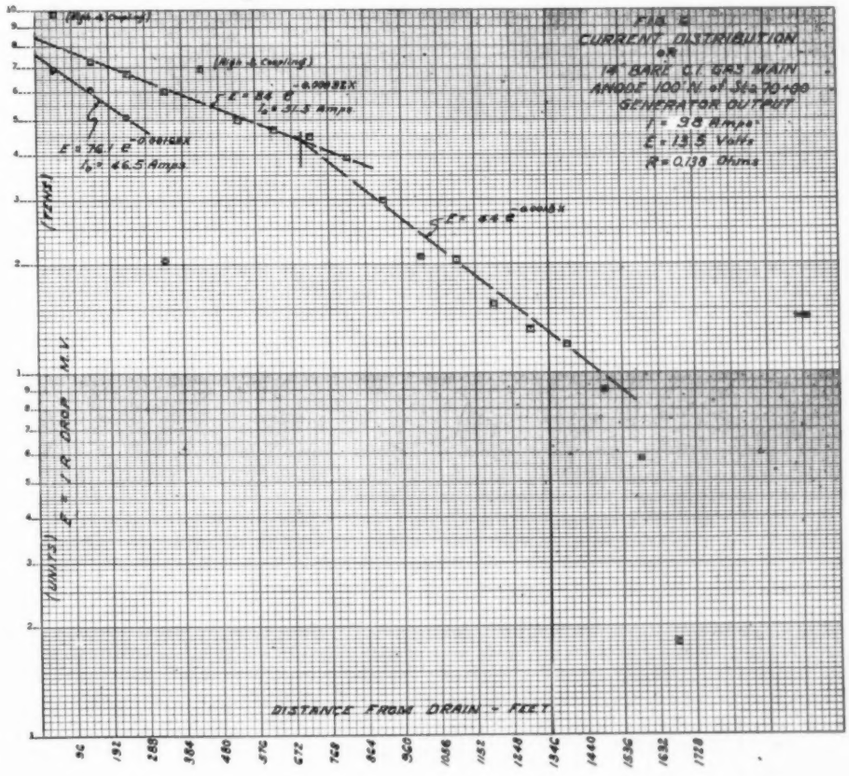
Figs. 1 and 2 represent the graphic relation between IR drop and distance from the negative return. Fig. 1 shows the distribution of a total drainage of 54 amp. and Fig. 2 shows the distribution over the same section of line with a total drainage of 100 amp. Figs. 3 and 4 are shown to illustrate the relative current distribution of the two different current values.

It is to be noted that the slope of the distribution curve remains unchanged regardless of current value. The value of the intercept changes in direct proportion to the amount of current drained.

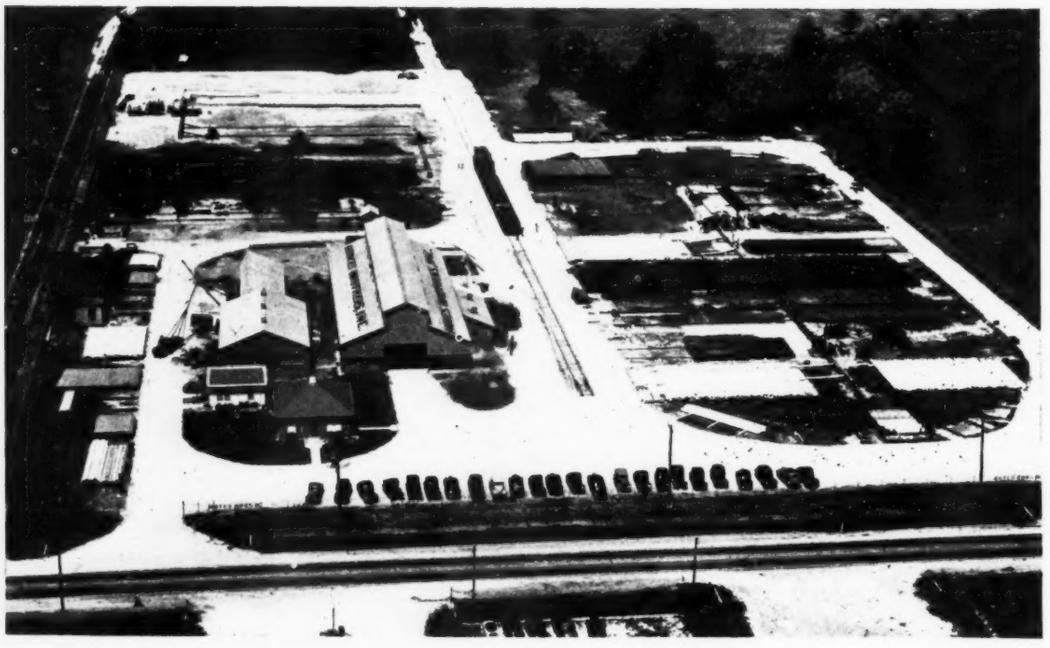
When a pipe line is subjected to a system of forced drainage, the current collected along its length and carried back to the negative return is a cumulative process. Therefore, once the current distribution relationship is established for a known current value the current values existing at any point on the line for any other drainage current can be determined from the functional relationship established.

It is to be noted that the magnitude of the current flow along the pipe de-

Fig. 6



PUTTING PERMANENCE IN PIPE



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cays exponentially as the distance from the point of drainage increases. From the relationship established by the data illustrated by Fig. 7 we have three separate curves all of the same general type. Each of the three curves for a particular section of line has the same slope differing only by the coefficient applicable to the functional relationship indicated.

The curves showing the trend indicated by IR drop and current values are both cumulative and are continuous whereas the current density curves are not continuous. A change of slope occurring in the current distribution curve causes an offset in current density value at the point of intersection. At the boundary between two different current distribution curves, the curve having the steepest slope will have the greatest current density at the point of slope change. It is believed by the writer, however, that the transition from one current density to another at these critical points will be gradual and not as abrupt as the graphic illustration indicates.

From the trend indicated by the foregoing data the distribution of current in combination with a fixed anode can be predicted for any reasonable drainage value. Hence, if two or more adjacent units are so located as to drain the same section of line if operating successively, it is assumed that the laws of superposition will apply when two or more adjacent units on the same line are operating simultaneously.

Consider two adjacent cathodic protection units so spaced that each unit would force current to flow from the soil to the pipe on the same section of line (Fig. 8). Curve A — B indicates the current density resulting from the operation of unit b, on the hypothetical section of pipe line; curve C — D indicates the current density resulting from unit a. From the law of superposition of currents and voltages[2] supplied over a network to a number of individual loads the following relation must exist:

(1) The current at any point in the network is equal to the algebraic sum of the currents that would flow if the individual load currents were considered in succession; and

(2) The voltage drop from the source to any point in the network is equal to the algebraic sum of the drops to that point, each drop being calculated on the basis of individual loads.

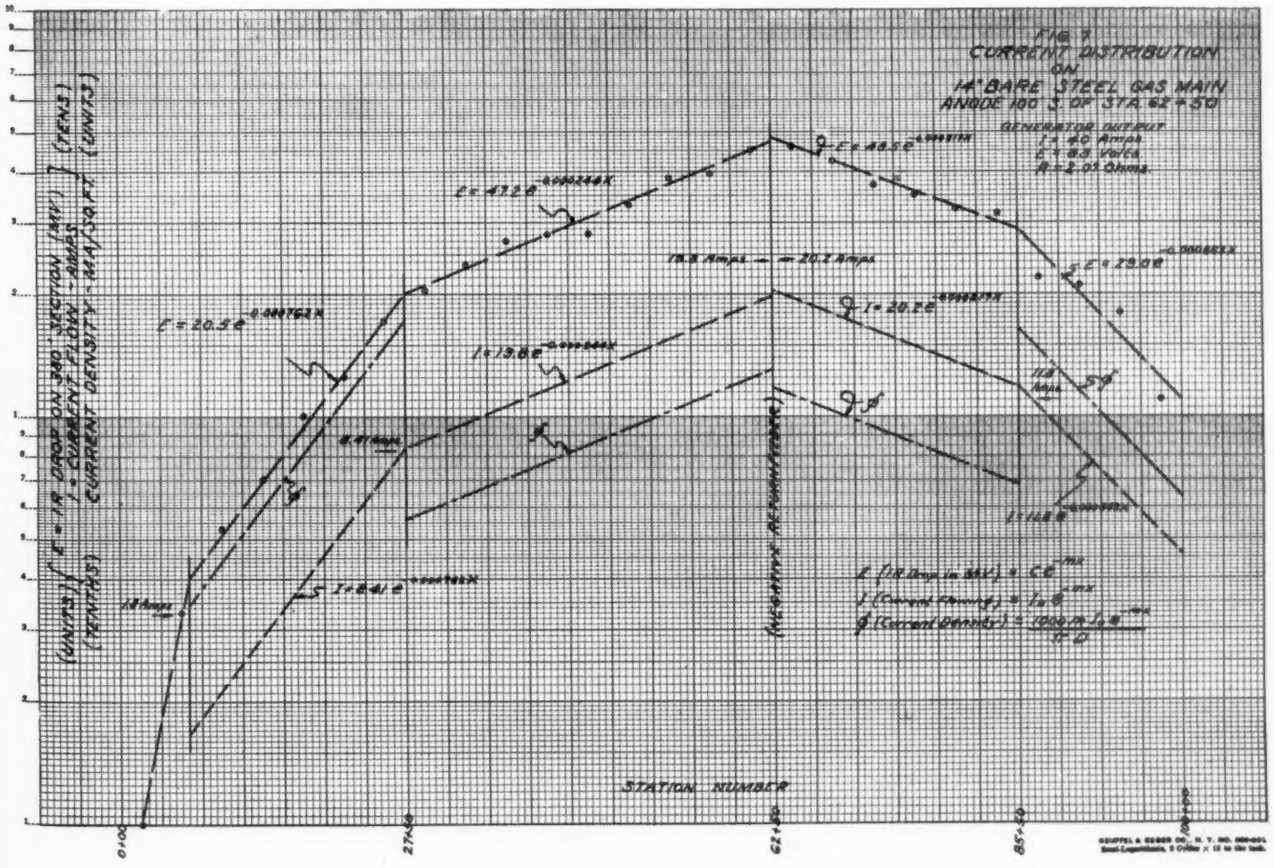
With units a and b operating simultaneously, IR drops measured along the line would follow the curve E — F and G — H. The composite current density resulting would correspond to the values shown by curve x — y. The pipe-to-soil potentials would follow the composite current density curve, being of like sign and additive whereas the IR drops measured along the pipe would be the algebraic summation of opposing voltages.

In view of the fact that only a single test unit was used the data that forms the basis of this discussion does not afford an opportunity to confirm the foregoing assumption based upon the law of superposition. The relationship of current flow established by these data, however, indicate that if two or more units had been in operation simultaneously this thesis would have been verified.

Conclusions

Faraday's Law of Electrolysis states that the amount of any element deposited at the electrodes is proportional to the quantity of electricity passed through the electrolyte. Therefore, some measurement of the quantity of electricity flowing per unit of surface area in contact with the electrolyte will reflect the electrical position of the structure relative to the magnitude of corrosion.

Fig. 7



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Based upon an analysis of the experimental data presented and discussed in this paper the following conclusions were drawn:

a. The current distribution on a pipe line exposed to a system of forced electrical drainage decays exponentially with the distance from the point of drainage.

b. A graphic solution of the observed data gathered by reading IR drops on a pipe line exposed to a system of forced electrical drainage indicates soil boundaries or changes in the character of the soil by a change in slope of the current distribution curve.

c. The current density at any point on a section of pipe line exposed to a system of forced electrical drainage is directly proportional to the current drained, the slope of the current distribution curve and the distance from the point of drainage.

d. The currents approaching and leaving a cardinal point on a pipe line exposed to a system of forced electrical drainage are equal.

Acknowledgment

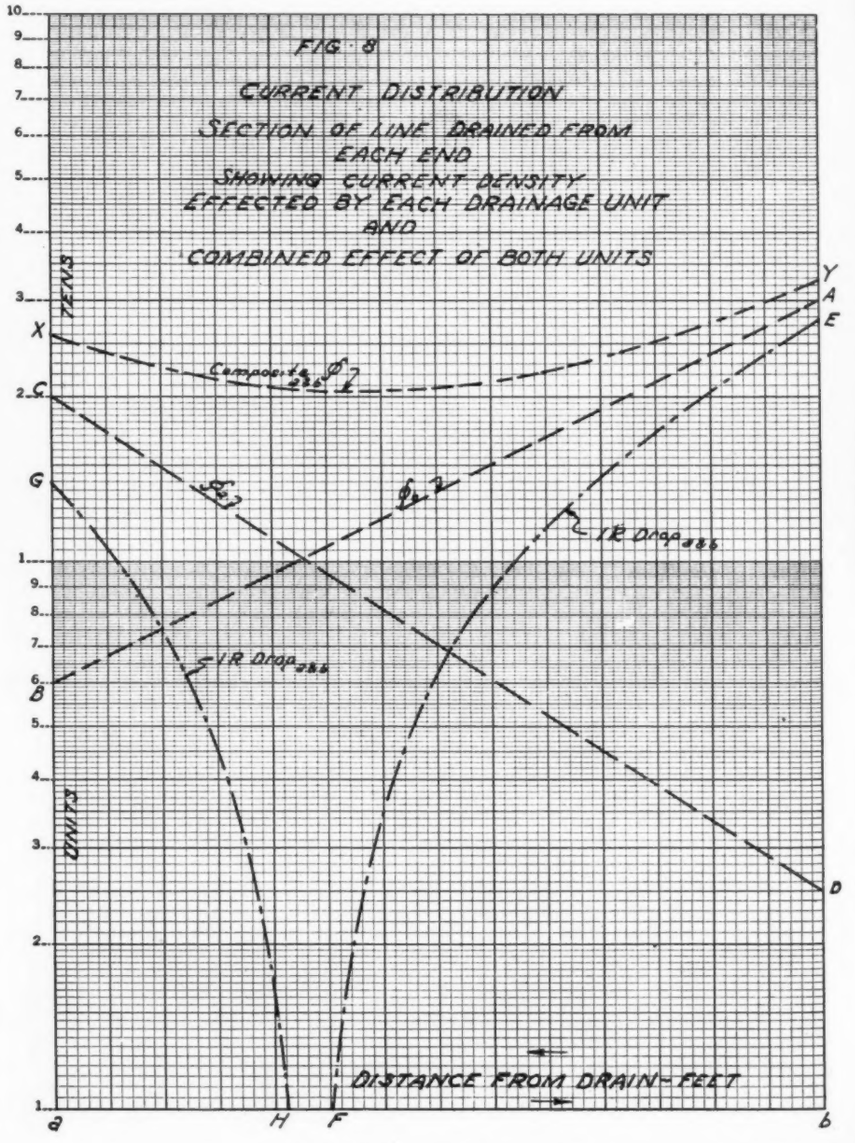
The experimental data that formed the basis of this report were taken from various surveys made on the pipe-line system of the Lone Star Gas Company. Permission to use these data is appreciated by the writer and it is hoped that the method described in this paper will be of benefit to the corrosion engineer. To Ed C. Connor, who collaborated in the preparation and editing of this paper, the writer is most grateful for the many helpful suggestions.

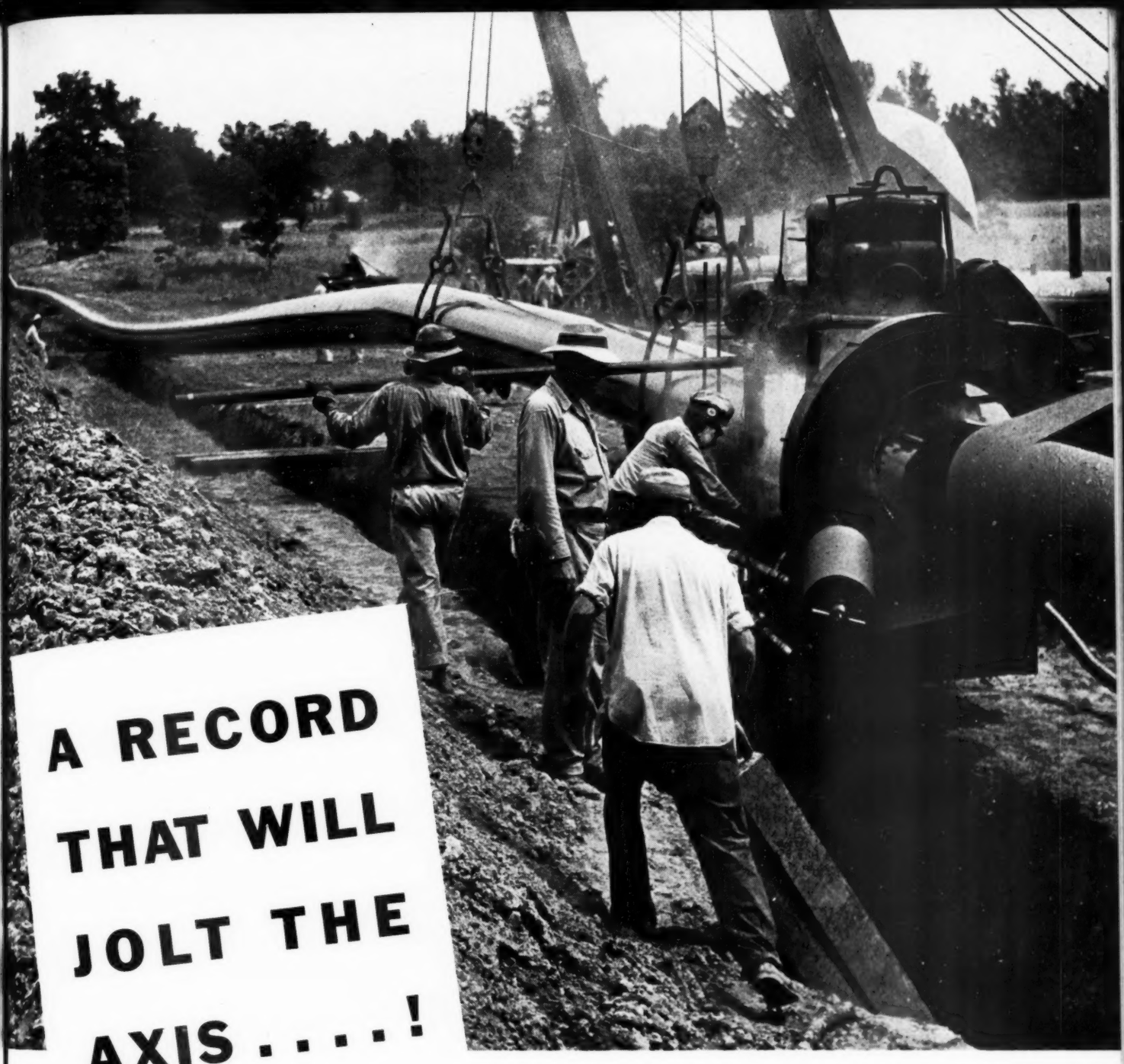
[1] "Electrical Instruments and Measurements in Solution of Electrolysis Problems," J. M. Pearson. Prepared for Bureau of Standards Corrosion Conference, 1937.

[2] *Handbook of Engineering Fundamentals*, O. W. Eshback. John Wiley and Sons, Inc.

☆ ☆ ☆

Fig. 8





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Cost of Pressure Vessels and Pressure Fractionating Columns*

By FRANK C. FOWLER, *Phillips Petroleum Company*
and
GEORGE GRANGER BROWN, *University of Michigan*

ABOUT a year ago Bliss[1] published cost data on process equipment and accessories accumulated with the aid of the Chemical Engineering Projects Committee of the American Institute of Chemical Engineers. Bliss did not cover plate fractionating columns and pressure vessels.

The cost data used in this paper were gathered as of late 1940 and January, 1941, which covers about the same period as the data used by Bliss; thus the two sets of data can be used together.

The data were compiled independently of Bliss and may differ to a limited extent.‡ Our data are based on actual costs in most cases and on actual quotations, f.o.b. fabricator's plant, with all discounts deducted, and do not include engineering overhead or erection, except in the case of insulation. Such costs are referred to as *net costs*. For *estimating costs* it is suggested that 10 percent be added to the *net costs*, to cover waste and the inevitable errors in any engineering estimate. Also, the costs of erection, including foundations, rigging, painting, and fire-proofing must be included in estimating total erected costs.

An effort has been made to include weight data for use in estimating freight charges and cost of stress relieving.

The numerous designs of pressure vessels and fractionating columns make the correlation of cost data on an entire vessel impractical. Therefore the net cost of an entire vessel has been broken down into the cost of the parts as fabricated into the vessel. For example the *net cost* of a fractionating column would consist of the following:

1. "Vessel Shell," which includes:
   (a) Shell with heads and skirt.
   (b) Handholes and manholes.
   (c) Nozzles and couplings.
   (d) Tray supports if the shell is for a column.
   (e) Stress relieving and X-ray inspection.
2. Bubble trays.
3. Platform, ladders, and handrails.
4. Insulation.
5. Freight.

Graphs offer a convenient and concise method of presenting cost data. Continuous curves were drawn when the points did not deviate more than 10 percent from the curve, as cost data are rarely accurate to a greater degree. Although the graphs are plotted as continuous lines covering all sizes, one must keep in mind that the costs apply only to the standard sizes as listed in the various catalogs and handbooks.

Vessel or Column Shell Cost

Under the heading, net cost of vessel or column shell, are included not only the net cost of the shell itself, but also heads, skirt, liners, manholes, handholes, nozzles, and couplings. An additional cost of tray supports must be added in figuring the net cost of a "Column Shell." In either case, it may be necessary to add the cost of stress relieving

*Published by American Institute of Chemical Engineers, *Transactions*, Vol. 39, No. 2, 1943.

[1]H. Bliss, *Trans. Am. Inst. Chem. Engrs.*, *37*, 763 (1941).

‡The only means of direct comparison is on the cost of column shells. Bliss gives costs of open steel towers varying from $0.15 per lb. to $0.10 per lb. as the weight varies from 1000 lb. to over 8500 lb. Our figure for net cost is $0.07 per lb. for carbon steel and $0.10 per lb. for alloy, A.S.T.M. specifications A-204 Grade A. The "Estimating Cost" for carbon steel vessels is therefore $0.077 per lb. compared with $0.10 per lb. as used by Bliss. These costs have been independently confirmed as of 1941.

Fig. 1

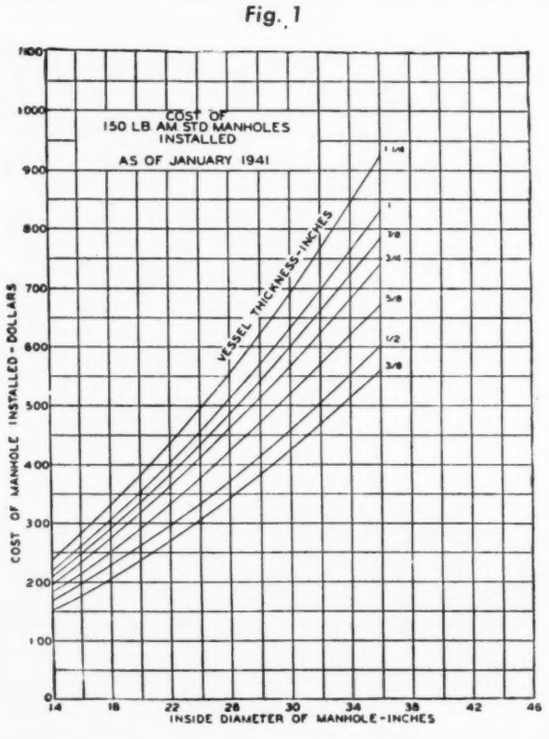
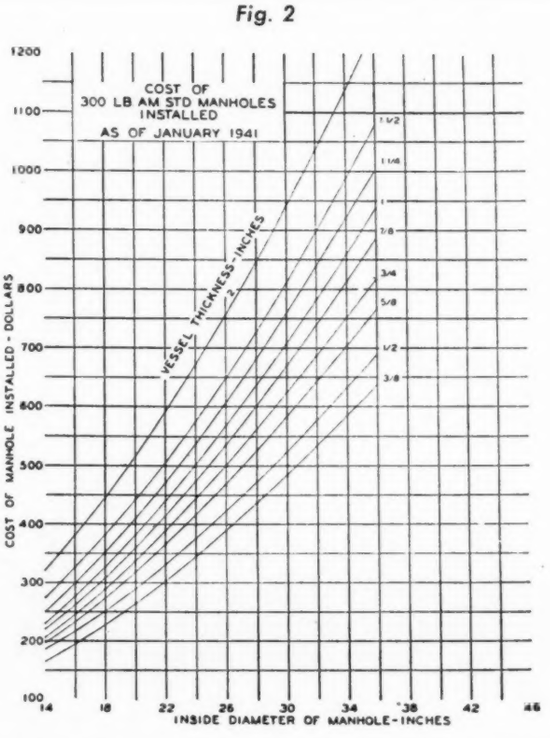
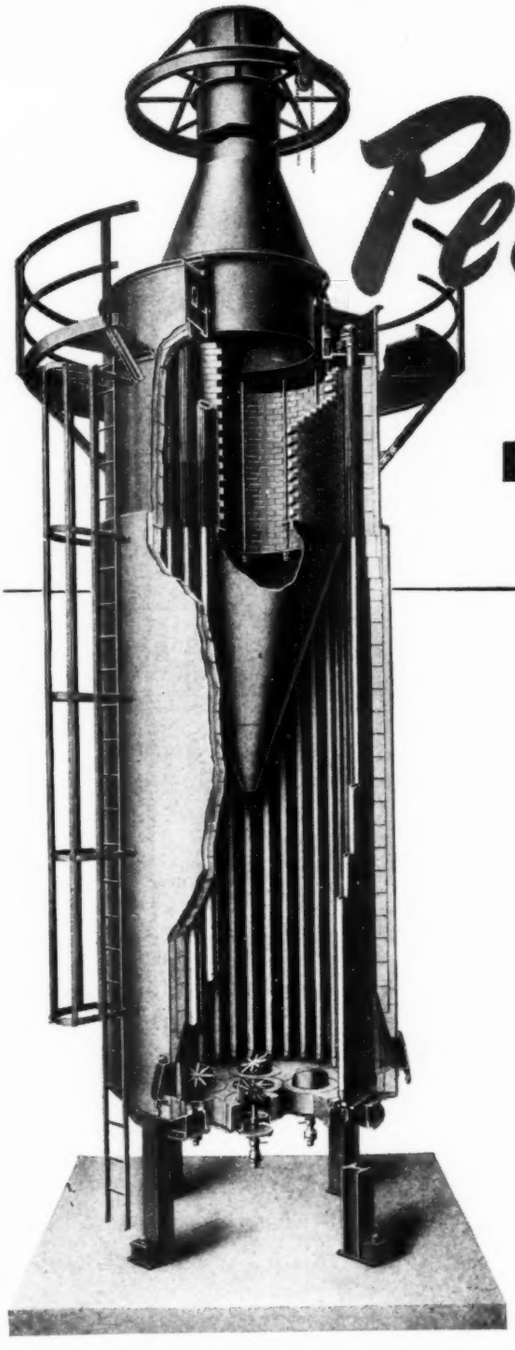


Fig. 2





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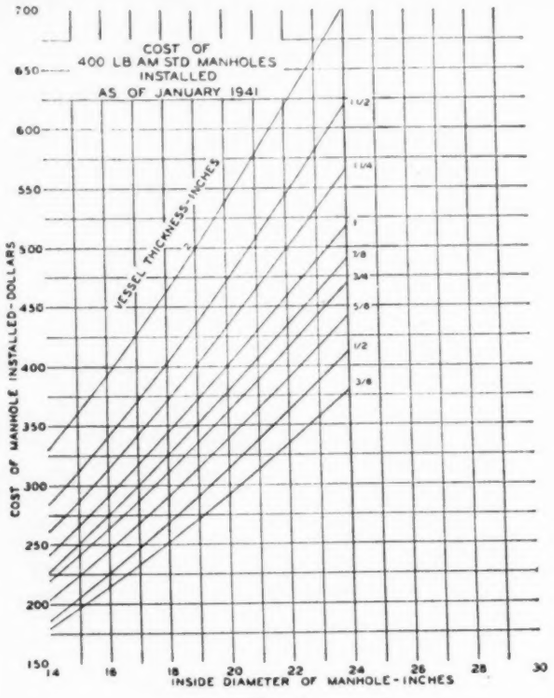

COST OF
400 LB AM STD MANHOLES
INSTALLED
AS OF JANUARY 1941
VESSEL THICKNESS - INCHES
COST OF MANHOLE INSTALLED - DOLLARS
INSIDE DIAMETER OF MANHOLE - INCHES

Fig. 3

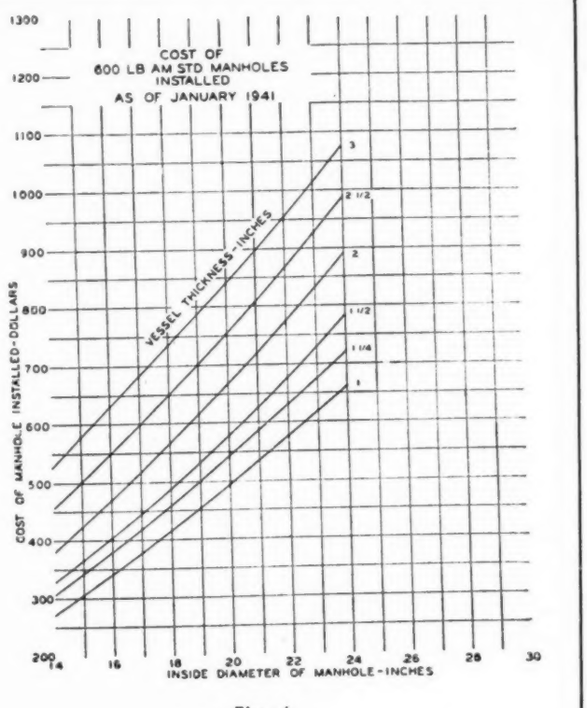

COST OF
600 LB AM STD MANHOLES
INSTALLED
AS OF JANUARY 1941
VESSEL THICKNESS - INCHES
COST OF MANHOLE INSTALLED - DOLLARS
INSIDE DIAMETER OF MANHOLE - INCHES

Fig. 4

and X-ray inspection, if the design specifies such treatment.

Net cost of shell, heads, and skirt is based on the weight. The weight can be calculated provided the dimensions including the shell thickness are known. The thickness of an unfired pressure vessel is generally calculated from the formula recommended by the A.P.I.-A.S.M.E. code. Net cost is then figured using as basis \$0.07 per lb. for steel and \$0.10 per lb. for a molybdenum-steel (A.S.T.M. specifications A-204 Grade A, firebox quality). These costs are lower than those given by Bliss.[1] Base angles for shells cost approximately \$0.15 per lb. for steel and \$0.20 for 5 percent chromium.

If alloy liners are used in the shell, the net cost may be determined as \$4.25 per sq. ft. for 5/64-in. liners and \$5.00 per sq. ft. for 7/64-in. liners. The weights of these liners are 3.2 and 4.5 lb. per sq. ft., respectively. Composition

Fig. 5

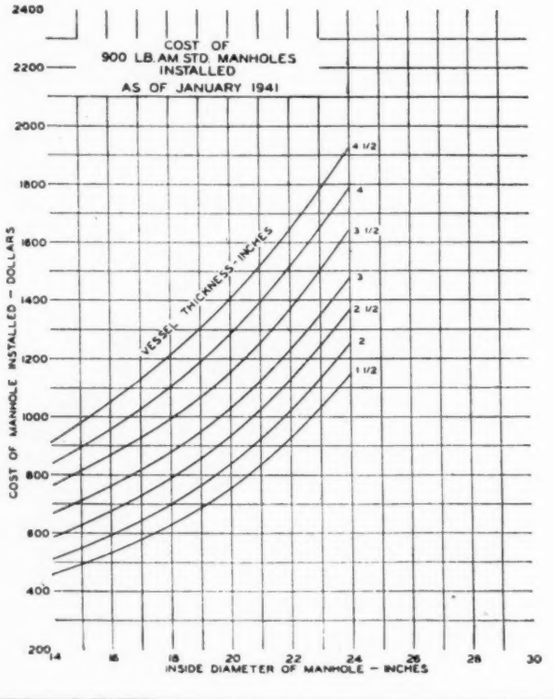
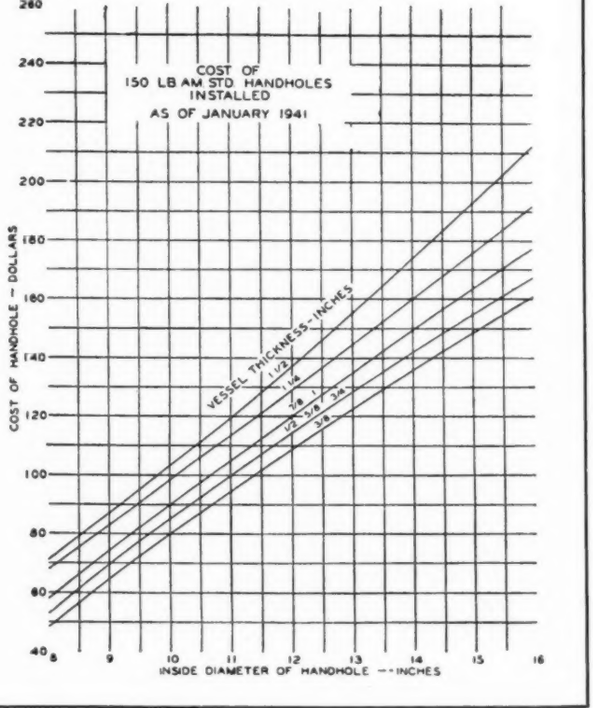

COST OF
900 LB AM STD MANHOLES
INSTALLED
AS OF JANUARY 1941
VESSEL THICKNESS - INCHES
COST OF MANHOLE INSTALLED - DOLLARS
INSIDE DIAMETER OF MANHOLE - INCHES

Fig. 6



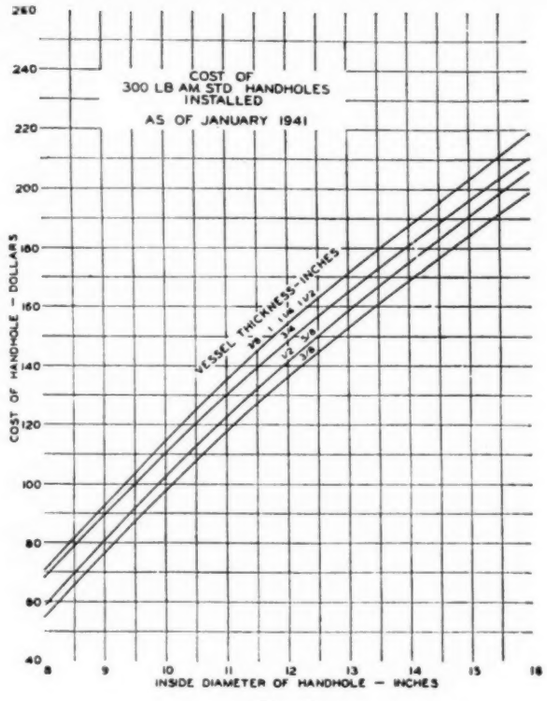


Fig. 7

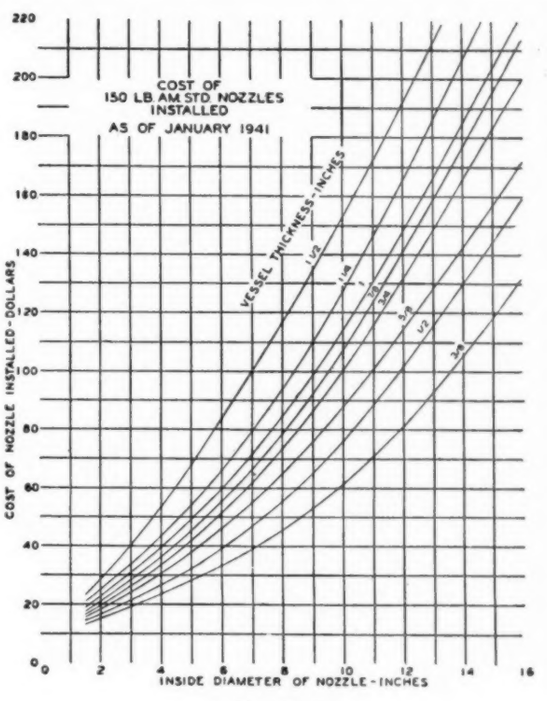

COST OF
150 LB AM STD NOZZLES
INSTALLED
AS OF JANUARY 1941
COST OF NOZZLE INSTALLED - DOLLARS
INSIDE DIAMETER OF NOZZLE - INCHES
VESSEL THICKNESS - INCHES

Fig. 8

of these liners corresponds to A.S.T.M. specification A-176, type 410.

The diameter, pressure rating, and vessel thickness determine the net cost of manholes, handholes, and nozzles. In Figs. 1 through 5 the net cost of manholes is plotted against inside diameter of manhole for various vessel thicknesses. These net costs include the net cost of manhole, net cost of cutting opening in vessel, and net cost of welding manhole in place. Thus they are referred to as net cost of manholes installed. Net cost of handholes installed is plotted against inside diameter of handhole for several vessel thicknesses in Figs. 6 and 7. Figs. 8 through 12 contain the *net cost* of nozzles installed versus inside diameter of nozzle for different vessel thicknesses.

The weight of the nozzles may be obtained from a manufacturer's catalog containing the weight of welding neck flanges. If the weight of manholes or

Fig. 9

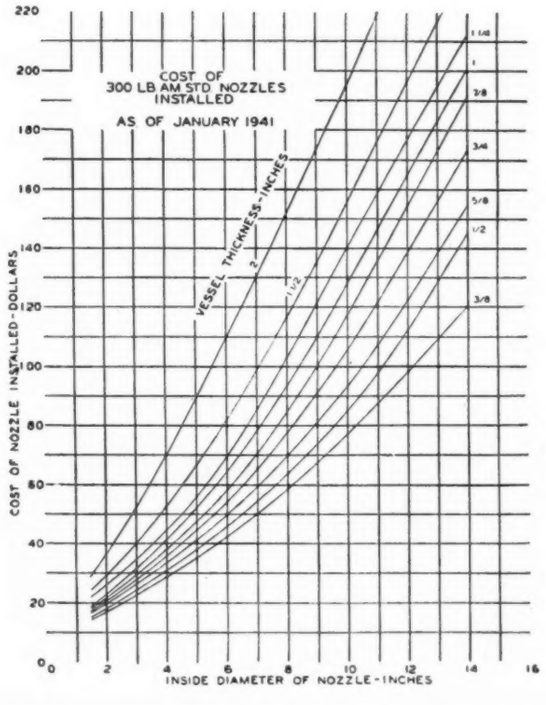
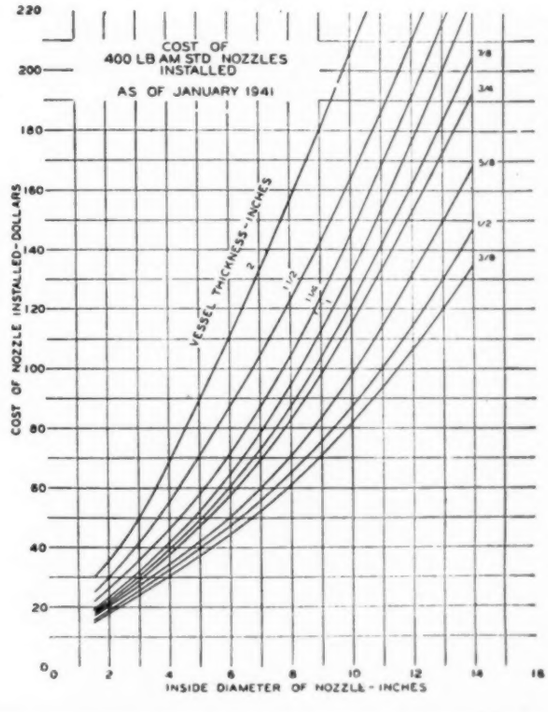

COST OF
300 LB AM STD NOZZLES
INSTALLED
AS OF JANUARY 1941
COST OF NOZZLE INSTALLED - DOLLARS
INSIDE DIAMETER OF NOZZLE - INCHES
VESSEL THICKNESS - INCHES

Fig. 10


COST OF
400 LB AM STD NOZZLES
INSTALLED
AS OF JANUARY 1941
COST OF NOZZLE INSTALLED - DOLLARS
INSIDE DIAMETER OF NOZZLE - INCHES
VESSEL THICKNESS - INCHES

handholes is desired, add to the weight of a welding neck flange the weight of a blind flange.

Alloy liners for nozzles and manholes are available at a cost of $0.17 per sq. in. for the liner, $0.25 per sq. in. for the facing, and $0.20 per sq. in. for the cover. Composition is the same as shell alloy liners.

Net cost of couplings installed is plotted against pipe size in Fig. 13. Weight may also be obtained from Fig. 13 by assuming 1 lb. per dollar.

If a fractionating column is under consideration, the net cost of tray supports is included as a part of the net cost of Column Shell. Fig. 14 indicates the weight of tray supports as a function of the diameter of the column. Net cost may be calculated from the figures of $0.15 per lb. for steel and $0.20 per lb. for 5 percent chromium.

If the "Vessel Shell" or "Column Shell" requires stress relieving, the net cost of such treatment can be estimated at 1 percent of the entire "Vessel Shell." However, a maximum cost for stress relieving of $500 should not be exceeded. X-ray inspection may be estimated at 3 percent of the net cost of "Vessel Shell."

Cost Cast-Iron Bubble Trays

A fractionating column will include bubble trays. The net cost of cast-iron bubble trays appears in Fig. 15 and the weight in Fig. 16. Both cost and weight have been plotted against column diameter for 12- and 24-in. plate spacings. Interpolation will give satisfactory results for 18-in. plate spacing. Net cost of cast-iron bubble trays consists of the cost of cast-iron decks, downpipes, round cast-iron bubble caps, packing and bolts.

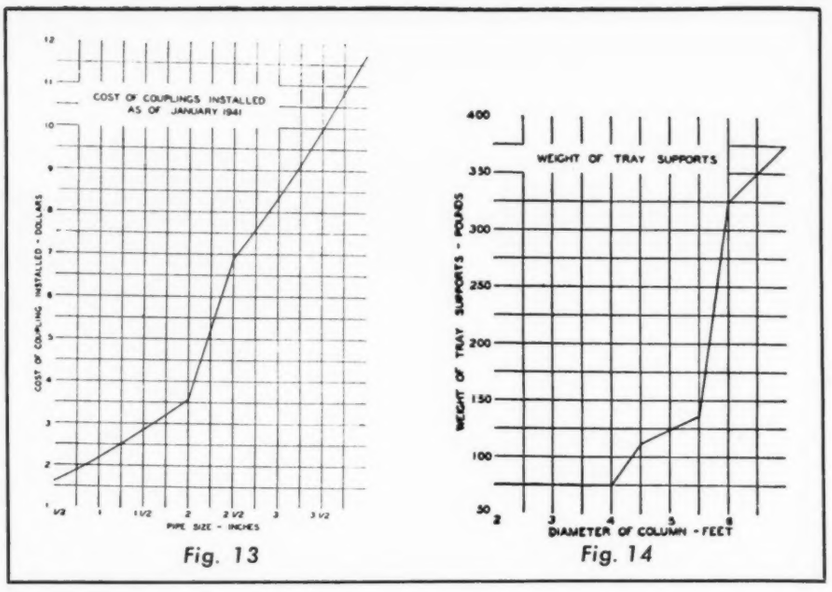

COST OF COUPLINGS INSTALLED AS OF JANUARY 1941
COST OF COUPLING INSTALLED - DOLLARS
PIPE SIZE - INCHES
WEIGHT OF TRAY SUPPORTS
WEIGHT OF TRAY SUPPORTS - POUNDS
DIAMETER OF COLUMN - FEET

Fig. 13 Fig. 14

Cost of Platforms, Handrails, and Ladders

Net cost of platforms, handrails, and ladders may be computed at $0.09 per lb. Weight of the ladder will run 30 lb. per ft., including the guard or basket. Handrail weighs 8 lb. per ft. In Fig. 17 the weight of platform and handrail is plotted versus column diameter.

Cost of Insulation

Insulation differs somewhat from the above items as it may be applied at the plant site rather than the fabricator's shop. Cost of insulation installed consists of the cost of insulation plus the cost of installation. Fig. 18 contains both items plotted as dollars per square foot of surface versus insulation thickness. When figuring the surface area use the outside surface of the insulation. Fig. 19 provides an approximate method

Fig. 11

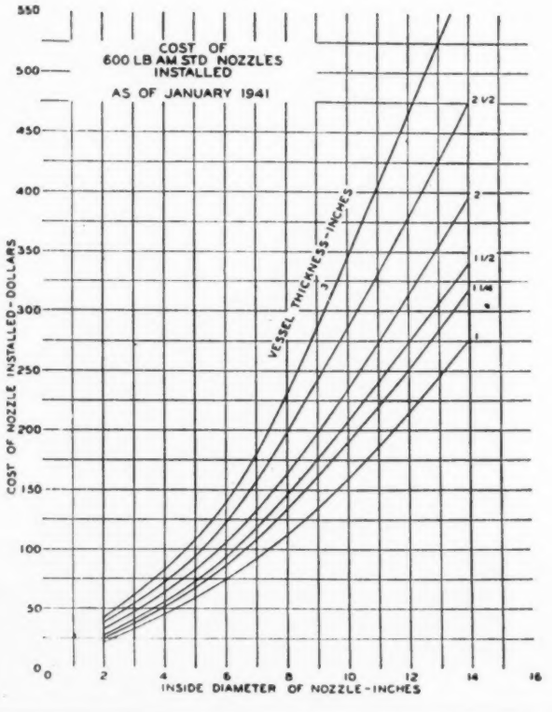
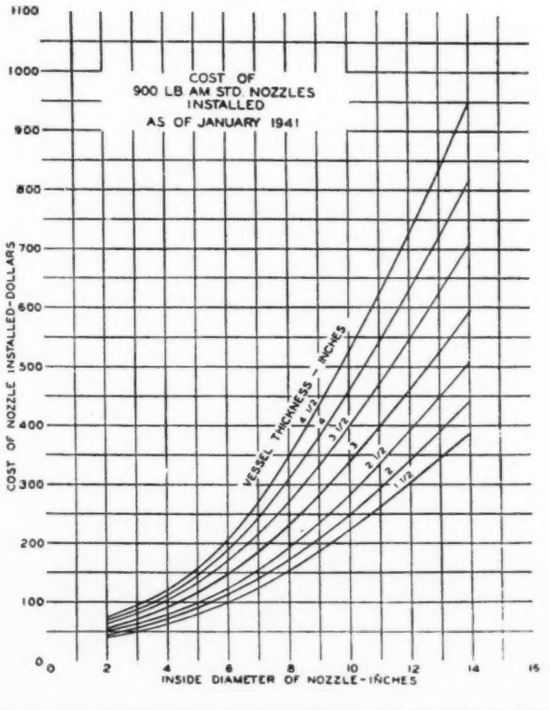
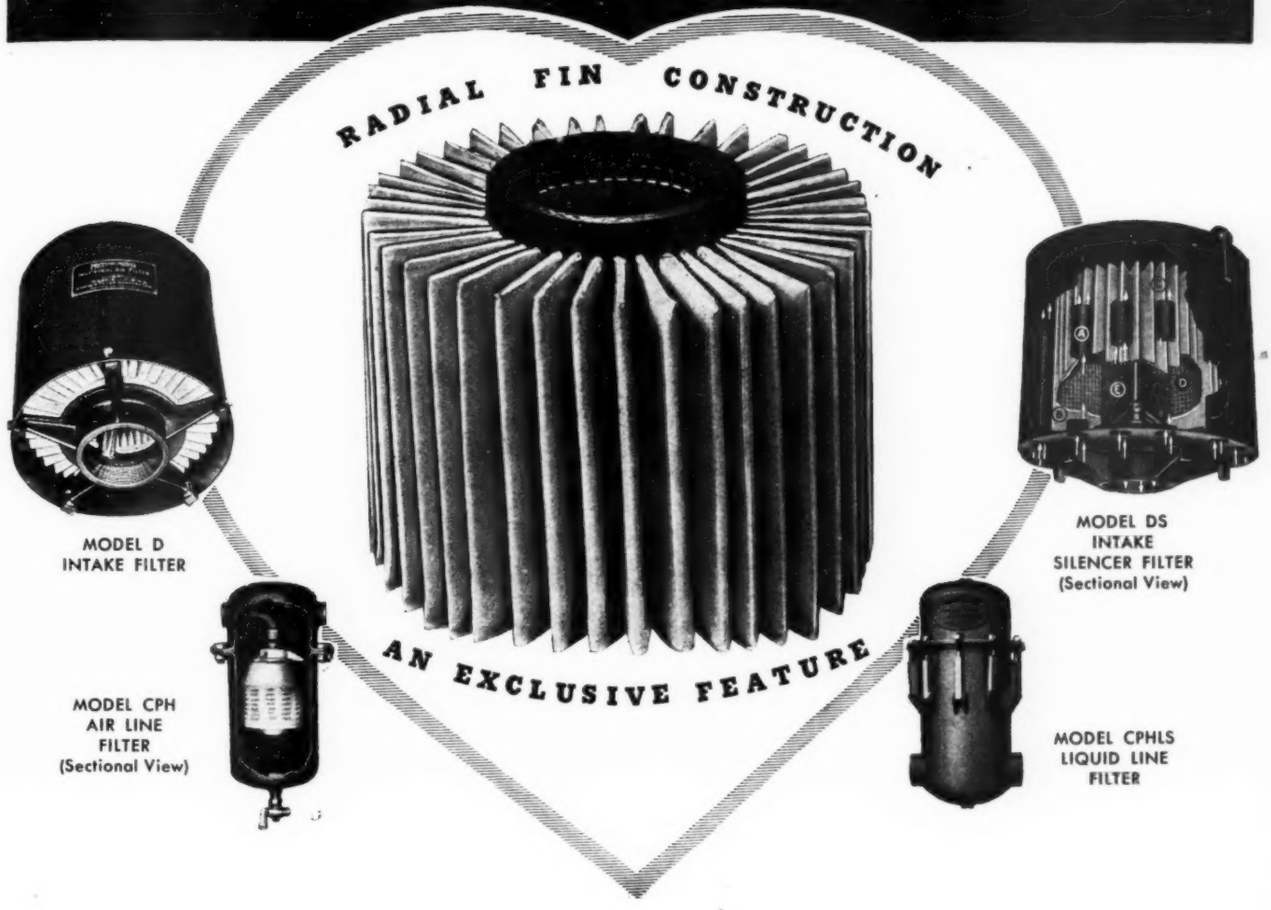

COST OF
600 LB AM STD NOZZLES
INSTALLED
AS OF JANUARY 1941
VESSEL THICKNESS - INCHES
COST OF NOZZLE INSTALLED - DOLLARS
INSIDE DIAMETER OF NOZZLE - INCHES

Fig. 12


COST OF
900 LB AM STD NOZZLES
INSTALLED
AS OF JANUARY 1941
VESSEL THICKNESS - INCHES
COST OF NOZZLE INSTALLED - DOLLARS
INSIDE DIAMETER OF NOZZLE - INCHES

THE HEART OF EVERY PROTECTOMOTOR


RADIAL FIN CONSTRUCTION
AN EXCLUSIVE FEATURE
MODEL D INTAKE FILTER
MODEL CPH AIR LINE FILTER (Sectional View)
MODEL DS INTAKE SILENCER FILTER (Sectional View)
MODEL CPHLS LIQUID LINE FILTER

RADIAL FIN CONSTRUCTION — an exclusive, patented feature found *only in Protectomotor* Air Filters for intake on engines and compressors and for pipe line filtration—has two major advantages: FIRST, it possesses a large area of filtering surface in relation to the overall size of the insert. An insert in the Radial Fin Construction only 11" high x 8¼" in diameter has an active filtering surface area of 1325 sq. inches. This means low resistance to air flow, high efficiency and long, maintenance-free life.

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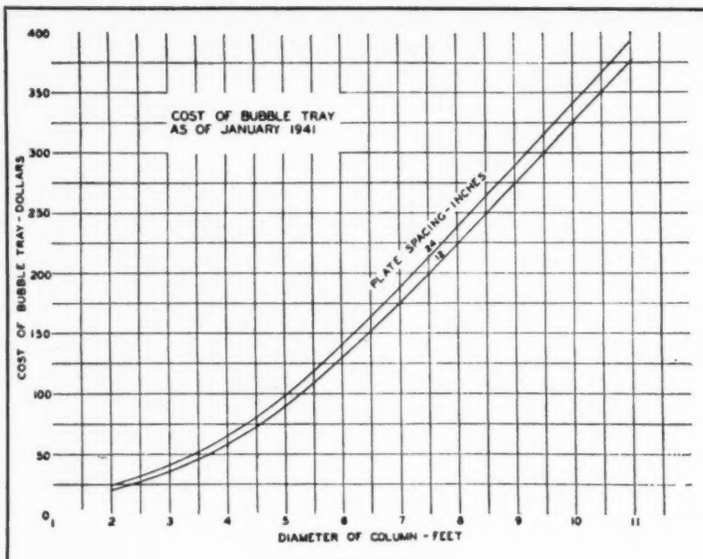


Fig. 15

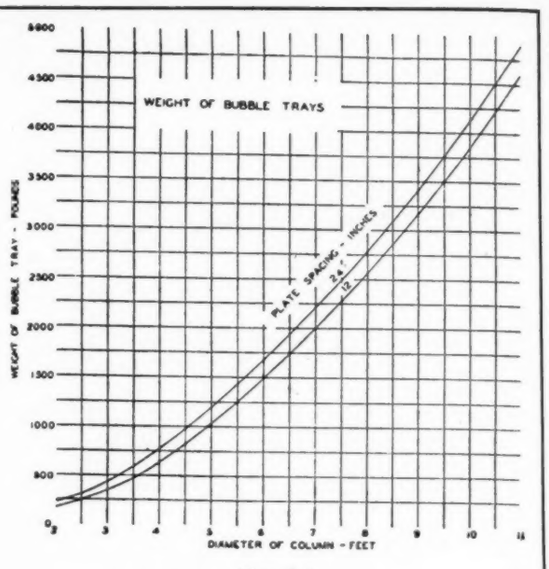


Fig. 16

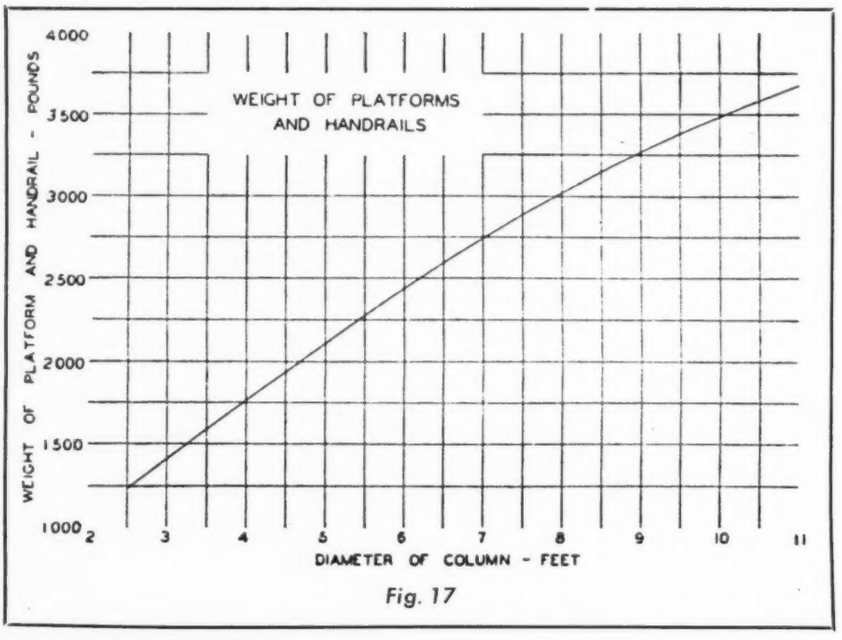


Fig. 17

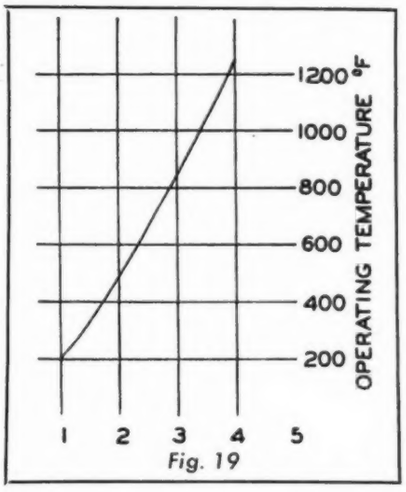


Fig. 19

110 percent of the total weight of the vessel or column.

Cost of Pressure Vessels and Fractionating Columns

It is recommended that a value equal to 110 percent of the *total net cost* of the vessel or column be used as the *estimated cost* of pressure vessels and fractionating columns.

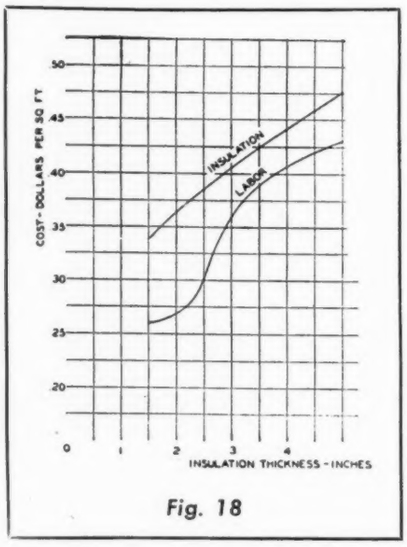


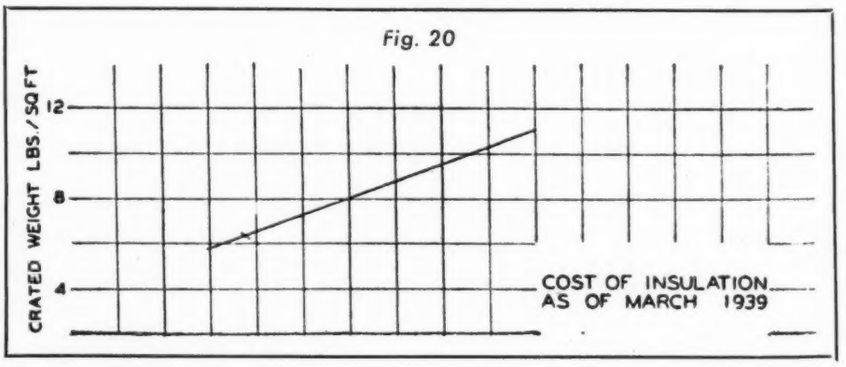
Fig. 18

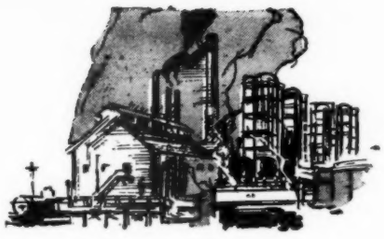
of estimating insulation thickness from operating temperatures. Crated weight of insulation is given in Fig. 20.

Freight

Freight charges are estimated upon

Fig. 20





Gases and Liquids

FOR SYNTHETIC RUBBER, TOLUOL, AVIATION GASOLINE, LUBRICANTS

Now, more than ever before,the handling of gases and liquids is a major task for the Petroleum Industry. It is an ever-changing problem involving new gases, new liquids, higher temperatures, higher pressures, greater volumes.

Inventive genius and ility to recognize a problem and lick it have always been associated with those in the Oil Industry. Due to their never-ceasing research, development, and production, we have the countless products so essential to war and peace.

Sustained development of compressors and pumps to handle the many and varied gases and liquids has permitted Ingersoll-Rand to help the Oil Industry solve many of its problems. Through the years, new machines have been built to meet ever-changing conditions—always built by men who appreciate the high standards of efficiency and reliability required by refiners and producers.

We will continue to meet and, where possible, to anticipate such requirements, no matter how severe these may be. Ingersoll-Rand Company, 11 Broadway, New York, N. Y.

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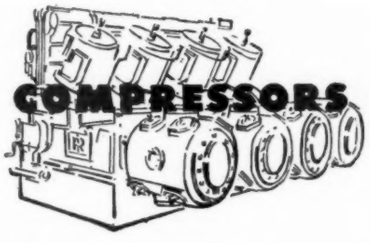
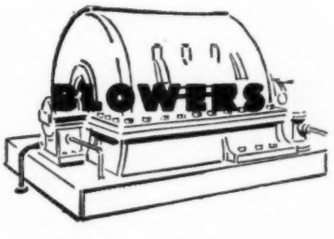
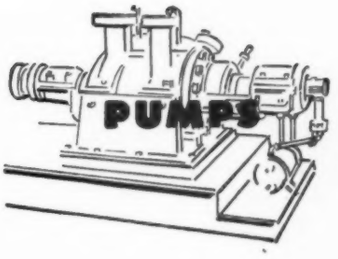






War Products From Natural Gas and Natural Gasoline*

By PAUL M. RAIGORODSKY and FRANK H. DOTTERWEICH
Natural Gas and Natural Gasoline Division, Petroleum Administration for War

THE growth of the petroleum industry during peace time was accompanied by the production and processing of such great quantities of crude oil that full consideration was not given to the effective utilization of the full range of petroleum raw materials in meeting the increasingly heavy burden of finished product requirements in war time. This condition, in part, resulted in the waste and devaluation of certain light petroleum derivatives together with a disregard of their use not only as a source of fuel and energy but as a potential source of many chemical and other useful products. Today the rapidly increasing tempo of war activities, accompanied by decreasing crude reserves, shortage of critical materials and transportation difficulties, dictate that all petroleum fractions shall be processed for their most efficient use in the war effort and under these conditions the processing of natural gas and natural gasoline becomes of the greatest importance. In this paper major attention will be given to the actual commercial processes by which these light petroleum fractions may be converted into vital war products.

The increasing importance and value of natural gas and natural gasoline in the war effort may be attributed, in part, to their comparatively large volumes available and the low critical material requirement for their production and processing. By modern methods of fractionation light hydrocarbons may be separated into relatively pure saturated hydrocarbons, valuable in their pure state as blending agents, or when processed by modern catalytic and thermal processes still more valuable as raw material giving remarkable yields of war products. Natural gas is invaluable not only as a source of war products but also in the proper development and production of recently discovered condensate fields due to the complexing phenomena of retrograde condensation.

The future should see increased discoveries of deep petroleum deposits of the "vapor state" type in which the recovered light petroleum fractions will be a greater percentage of the total petroleum products than heretofore, thereby insuring increasing supplies of natural gas and natural gasoline and perpetuating their use in developments that have been accelerated, and in some cases, forced upon the petroleum industry during war time.

These conditions, relative to the supply and scientific developments, in natural gas and natural gasoline operations have made possible the production of war products, the most important of which are synthetic rubber, carbon black, aviation fuel, and explosives. Many of these developments cannot be reviewed herein due to wartime restrictions, but a general report on some of the more important commercial developments and of processes available for commercial development will to a certain degree show that natural gas and natural gasoline play a most important role in the war.

*Presented before Natural Gasoline Association of America, Dallas, Texas, April 15, 1943.

Butadiene by Catalytic Dehydrogenation

In the production of butadiene by the catalytic dehydrogenation of normal butane the commercial process of the greatest importance is the Houdry one-stage and combined two-stage dehydrogenation catalytic processes. The dehydrogenation occurs in six special catalytic reactors, operated under subatmospheric pressure and at carefully controlled temperatures.

The two-stage process, which has been reported[1], is now being constructed by the Standard Oil Company of California, which should go on stream in the near future.

The one-stage process will be used in one of the Sun Oil Company's plants, which should go into commercial production of 15,000 tons of butadiene per year, early in May.

The one-stage process differs from the original two-stage process by injecting the fresh butane feed with the recycled butane-butene mixture. In this set-up there would be two cases operating on butane-butene for ten minutes or less, two cases regenerating, and two cases purging. The reactants flow only upward through the catalyst bed, thereby effecting economies in the size and number of connections to the cases. This method necessitates increased amounts of air and butane or the injection of 746 bbl. per day of normal butane to manufacture 15,000 tons of butadiene per calendar year, against 660 bbl. originally reported. The most astonishing fact concerning this plant is its construction with practically all second-hand material. New critical material requirements have been limited to small items such as the large vacuum cylinders on compressors, some valves, instruments, and other similar materials. It is very interesting to note the material requirements for this plant when compared with the original estimated requirements. The complete amount of critical material, which it was necessary to purchase under priority for the entire butadiene plant, including dehydrogenation and purification sections and also auxiliary equipment, such as new boilerhouse, electric power services, water services, etc., amounted to 719.8 tons as against the original estimate of 850.6 tons.

Many refinery conversion projects in the "quickie" program have been canceled including projects using the Houdry Process. It was stated and should be noted that the reason for cancellation of the Houdry units was entirely due to the late date of their construction. A pilot plant with one case of commercial design and size is in continuous operation at Marcus Hook, Pennsylvania, and operating data substantiates claims relative to the efficiency of the Houdry Process.

This process continues to be most desirable in the production of butadiene because butane and not butylene is the charging stock. Large quantities of butane are available in many localities,

[1]"Houdry Two-stage Dehydrogenation Catalytic Process for Manufacture of Butadiene," C. H. Thayer, R. C. Lassiat, and E. R. Lederer, *National Petroleum News*, September 30, 1942.

TABLE I

Nitro compounds

Air → Ammonia ← Natural Gas

Ammonia nitrate	Nitric acid	Mixed acids (sulphuric and nitric)

Propellants	Detonators and fuses	High explosives		Intermediate boosters
Smokeless powder	Nitro mannite	Trinitrotoluol TNT	Trinitroanisol	Tetranitro methyaniline
Cordite		Dinitrotoluol DNT	Penthrite	Trinitro aniline, TNA
		Amatol, TNT and ammonium nitrate	Nitrostarch	Hexanitro diphenylamine
		Explosive D, picric acid and ammonium picrate	Nitrosugars	
			Nitroisobutylglycerine nitrate	

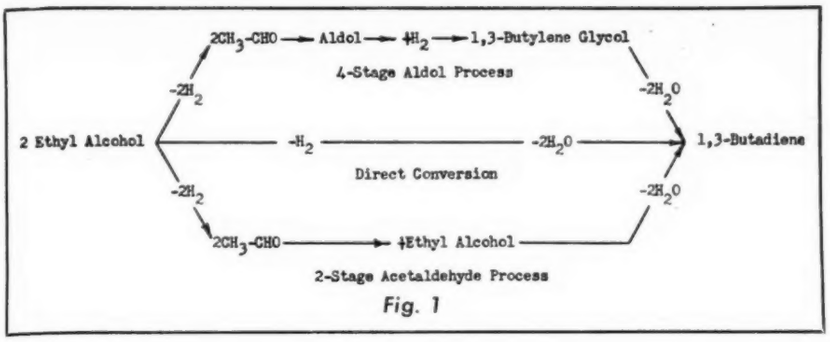


Fig. 1

whereas available butylenes are scarce due to great demand for the aviation fuel program.

Butadiene from Ethyl Alcohol

Butadiene can be made from a number of diversified raw materials coming from agricultural and mineral sources and one of the most important raw materials available from both sources is ethyl alcohol.

The many possible processes available to convert ethyl alcohol into butadiene have been carefully reviewed and reported[2]. In this reference, these processes are classified into the following general groups:

1. Direct conversion of ethyl alcohol.
2. The aldol method.
3. Ethylene methods.
4. Acetylene methods.
5. Acetaldehyde condensations and conversion to butadiene.
6. Crotonaldehyde methods.

When natural gas is the raw material in the production of ethyl alcohol, its separation is confined to the following groups: dry gas, ethane-propane mixture, and natural gasoline. The ethane-propane mixture is thermally cracked into ethylene, which is reacted first with sulphuric acid, then with water, with ethyl alcohol as the product. This method is being used commercially to produce ethyl alcohol with the sulphuric acid being recovered, concentrated, and recycled.

Under other conditions when natural gas is the raw material the Direct Conversion, Aldol, and Acetaldehyde Condensation Methods are of importance.

These methods may be summarized as illustrated in Fig. 1.

It appears that at the present time alcohol manufactured from natural gas is not being used to produce butadiene. A plant is now in commercial production of butadiene from alcohol, however, with most encouraging yields using the two-stage method of conversion. It is interesting to note that in this plant the original design called for the production of alcohol from ethylene as previously indicated.

Regenerative Furnace Method

Petroleum Chemicals, Inc., has designed and built at their Baltimore plant a semi-commercial unit for the cracking of hydrocarbons by regenerative heating and for the separation and purification of the olefines produced. This type furnace was partially developed by the Tennessee Eastman Corporation under the supervision of Dr. R. L. Hasche[3] in connection with the production of acetylene by thermal cracking and has been adapted to the production of butadiene utilizing heavy naphtha as charging stock, and it is reported that a yield of 5.2 weight percent of butadiene was obtained.

For a discussion of the furnace together with its operation, reference is made to Fig. 2.

During the firing cycle, fuel gas and air are fed to the pressure burner at (A). Combustion is complete in the fire box at (B), the air supply may be closely regulated to give practically no excess air and the products leave through the stack (C), steam purges at the end of the cracking, and firing cycles prevent contamination of the product. The vaporized feed at about 500°F. is mixed with low-pressure steam and fed to the furnace at (D). Cracking is effected over the carborundum checker work, previously brought to heat in the firing period, and the cracked products on leaving the furnace are cooled by means of direct water sprays to about 130°F., then conducted to concentration and purification apparatus.

The development of the modern regenerative furnace is not only of importance as a possible method of butadiene production from condensate, but offers a splendid method by which by-product ethane-propane mixtures may be cracked to ethylene, propylene, and benzene mixtures. These raw materials are of importance in the manufacture of aviation fuel and this subject will be discussed herein.

It is reported that the operation of the regenerative furnace is superior to the commercial method of tubular cracking when overall yields of desirable unsaturated hydrocarbons are of importance.

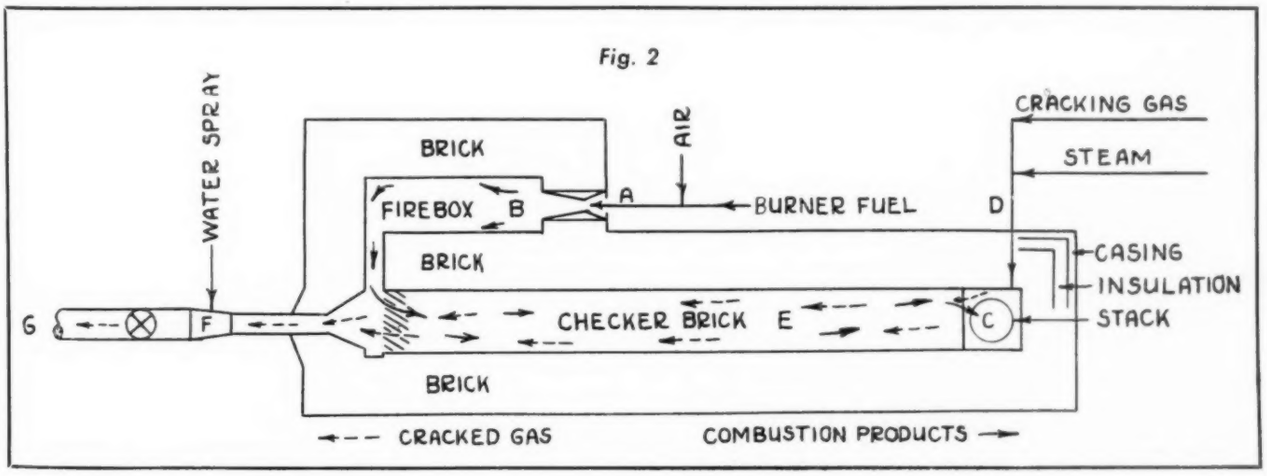
Carbon Black

The development of synthetic rubber and its increased production is being accompanied by increased production of new types of carbon black essential in

[2] "Manufacture of Butadiene from Ethyl Alcohol," J. A. Gamma, and T. Inouye, *Chemical and Metallurgical Engineering*, December, 1942, and January, 1943.

[3] "Production of Acetylene by Thermal Cracking of Petroleum Hydrocarbons," R. L. Hasche, *Chemical and Metallurgical Engineering*, July, 1942.

Fig. 2



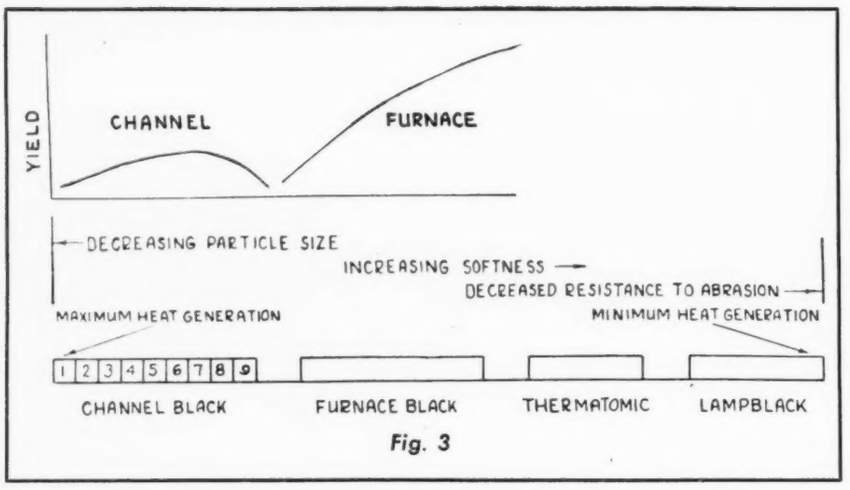


Fig. 3

compounding procedures. In the past, natural gas has been the raw material in the production of channel blacks required in compounding natural rubber, and this raw material continues to supply the newer types of carbon black, i.e., furnace and thermatomic blacks, which are required in compounding synthetic rubber.

The necessity of increased production of furnace and thermatomic blacks may be explained by reference to Fig. 3 and a discussion of the properties of carbon black when compounded with natural and synthetic rubber.

With crude rubber available, channel blacks were satisfactory for blending purposes in automobile tire manufacture. These blacks may be classified as indicated (refer to Fig. 3), and it will be noted that carbon with the smallest particle size and with a maximum of heat generation and abrasive resistance would be the hardest. Increased particle size is accompanied by decreased heat generation and abrasive resistance. In addition it should be noted that yields of carbon black are a minimum with the fine particle size, increasing to a maximum with increasing particle size up to a certain point and then decreasing with the maximum particle size in channel operations. From these grades of channel black a suitable black would be obtained to give maximum wear resistance to various size tires in which the geometric shape had pronounced effect upon heat transfer conditions. This suggests that the larger, softer, particle size black with decreased abrasive resistance was necessary in large truck and bus tires to give an overall maximum wearing property, whereas the hard, smaller-size black was preferable in the manufacture of normal-size automobile tires.

With the advent of synthetic rubber, changes in carbon black production and blending were imminent. This, in part, was brought about because synthetic rubber has a low tensile strength, necessitating the use of carbon black in greater amounts and in certain portions of the tire and tube where heretofore it was not used.

In addition, synthetic rubber does not bounce to the same extent as natural rubber, resulting in a greater portion of energy being converted into heat. These conditions dictate that heat generation be kept to a minimum by increasing particle size and decreasing hardness and abrasive resistance to impart an overall maximum wearing quality to synthetic rubber products. To obtain these softer blacks, processes other than the channel must be employed and today large quantities of this material are being manufactured by the furnace and thermatomic methods.

The furnace process may briefly be explained by reference to Fig. 4. In this process natural gas is burned under carefully controlled conditions with definite proportions of air to give the quality of black desired. The products are piped from the furnace to cyclone and electrical precipitation apparatus where the black is recovered and prepared for shipment. In general the efficiency of this process increases with increased particle size with yields of from 3 to 20 lb. per M. cu. ft. of gas against a yield of from 1 to 5 lb. in the channel process.

Soft blacks may also be manufactured by thermatomic cracking operations. In this method carbonaceous vapors or gases are heated to a decomposition temperature by external heating with or without air in the forming chamber.

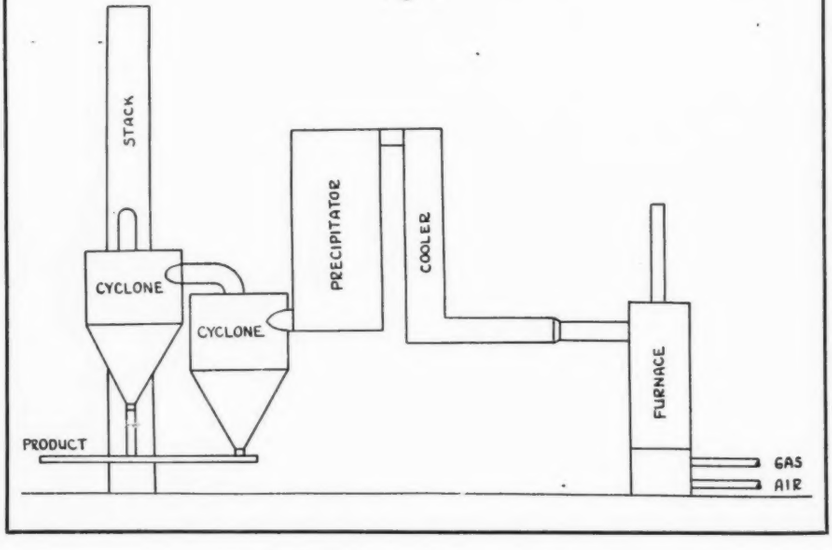
These blacks with their great range in properties have allowed for the development of a suitable blending material for our relatively new types of synthetie rubber, not only imparting comparative abrasive and wear resistance when compared with natural rubber but marked increased resistance to aging and tear resistance together with chemical inertness.

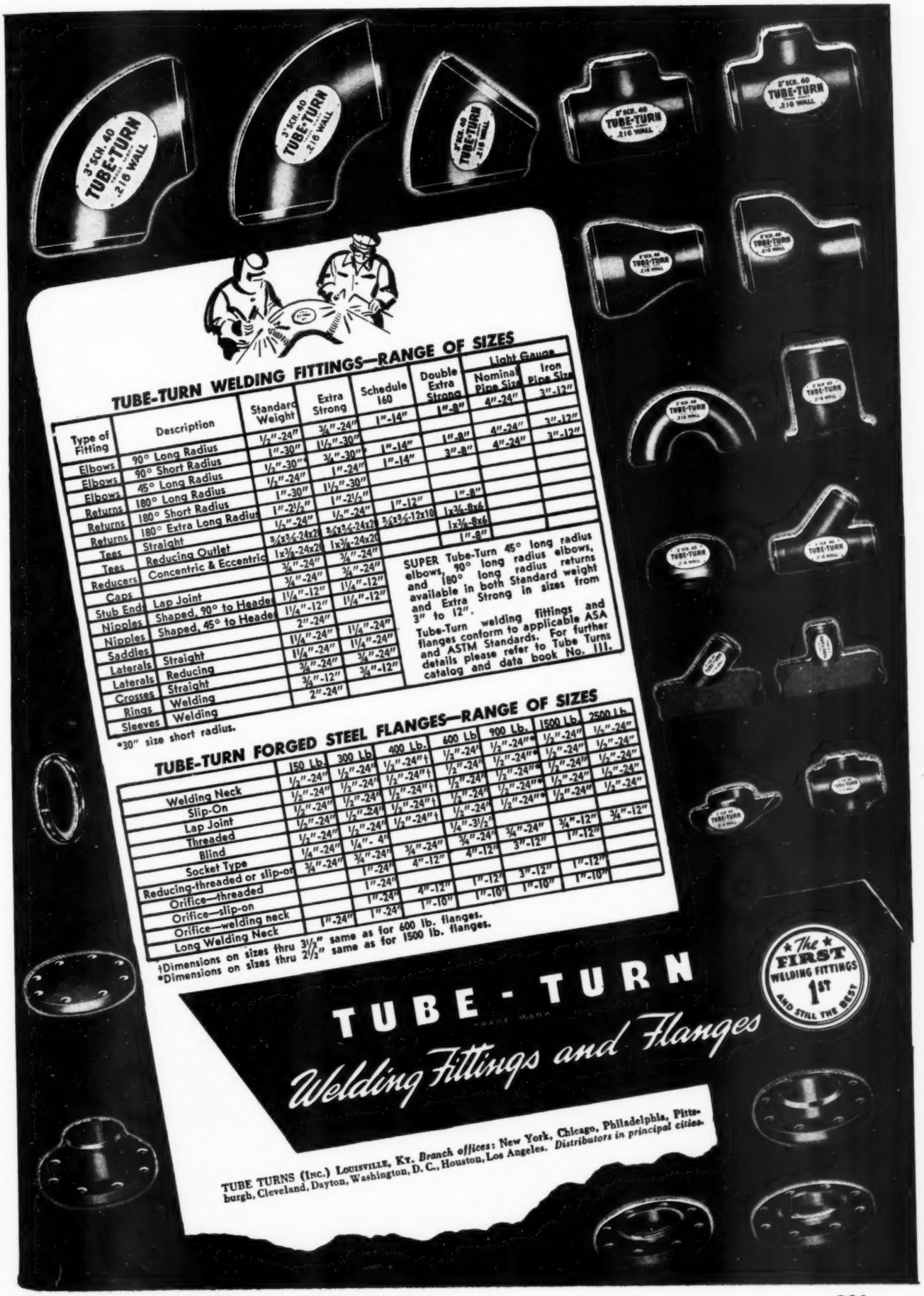
Aviation Gasoline From Derivatives

Aviation gasoline continues to maintain the greatest interest in petroleum operations and too much emphasis cannot be placed upon the many available methods and raw materials by which our supplies of aviation gasoline may be supplemented. With the ever-increasing demand for aviation gasoline, together with the critical shortage of new materials and decreasing crude reserves, available quantities of natural gasoline and condensate become of extreme value when their synthesis into aviation fuels is investigated.

The participation of the natural gasoline industry in the production of aviation fuel needs no introduction; the economics and practicability of the use of natural gasoline is verified in that at the present time 30,000 bbl. per day are going into the manufacture of 87-, 91-,

Fig. 4





TUBE-TURN WELDING FITTINGS—RANGE OF SIZES

Type of Fitting	Description	Standard Weight	Extra Strong	Schedule 160	Double Extra Strong	Light Gauge	
						Nominal Pipe Size	Iron Pipe Size
Elbows	90° Long Radius	½"-24"	⅜"-24"	1"-14"	1"-8"	4"-24"	3"-12"
Elbows	90° Short Radius	1"-30"	1½"-30"				
Elbows	45° Long Radius	½"-30"	¾"-30"	1"-14"	1"-8"	4"-24"	3"-12"
Returns	180° Long Radius	1"-24"	1"-24"	1"-14"	3"-8"	4"-24"	3"-12"
Returns	180° Short Radius	1"-30"	1½"-30"				
Returns	180° Extra Long Radius	1"-2½"	1"-2½"				
Tees	Straight	½"-24"	½"-24"	1"-12"	1"-8"		
Tees	Reducing Outlet	¾x¾-24x24	¾x¾-24x24	¾x¾-12x10	1x¾-8x6		
Reducers	Concentric & Eccentric	1x¾-24x24	1x¾-24x20		1x¾-8x6		
Caps		¾"-24"	¾"-24"		1"-8"		
Stub End	Lap Joint	¾"-24"	¾"-24"				
Nipples	Shaped, 90° to Header	1¼"-12"	1¼"-12"				
Nipples	Shaped, 45° to Header	1¼"-12"	1¼"-12"				
Saddles		2"-24"					
Laterals	Straight	1¼"-24"	1½"-24"				
Laterals	Reducing	1¼"-24"	1¼"-24"				
Crosses	Straight	¾"-24"	¾"-24"				
Rings	Welding	¾"-12"	¾"-12"				
Sleeves	Welding	2"-24"					

SUPER Tube-Turn 45° long radius elbows, 90° long radius elbows, and 180° long radius returns available in both Standard weight and Extra Strong in sizes from 3" to 12".

Tube-Turn welding fittings and flanges conform to applicable ASA and ASTM Standards. For further details please refer to Tube Turns catalog and data book No. 111.

*30" size short radius.

TUBE-TURN FORGED STEEL FLANGES—RANGE OF SIZES

	150 Lb.	300 Lb.	400 Lb.	600 Lb.	900 Lb.	1500 Lb.	2500 Lb.
Welding Neck	½"-24"	½"-24"	½"-24"†	½"-24"	½"-24"*	½"-24"	½"-24"
Slip-On	½"-24"	½"-24"	½"-24"†	½"-24"	½"-24"*	½"-24"	½"-24"
Lap Joint	½"-24"	½"-24"	½"-24"†	½"-24"	½"-24"*	½"-24"	½"-24"
Threaded	½"-24"	½"-24"	½"-24"†	½"-24"	½"-24"*	½"-24"	½"-24"
Blind	¼"-24"	¼"- 4"		¼"-3½"			
Socket Type	⅜"-24"	¾"-24"	¾"-24"	¾"-24"	¾"-24"	¾"-12"	¾"-12"
Reducing-threaded or slip-on		1"-24"	4"-12"	4"-12"	3"-12"	1"-12"	
Orifice—threaded		1"-24"					
Orifice—slip-on		1"-24"	4"-12"	1"-12"	3"-12"	1"-12"	
Orifice—welding neck		1"-24"	1"-10"	1"-10"	1"-10"	1"-10"	
Long Welding Neck	1"-24"						

†Dimensions on sizes thru 3½" same as for 600 lb. flanges.
*Dimensions on sizes thru 2½" same as for 1500 lb. flanges.

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and 100-octane fuel, and by the end of 1943 this figure will approach 70,000 bbl. per day. In addition it is estimated that approximately 175,000 bbl. per day of natural gasoline and condensate are going into motor fuel, and a considerable portion of this may be made available for aviation fuel production. The imminent shortage of petroleum products must not be construed as being accompanied by a shortage of natural gasoline and condensate. On the contrary sufficient raw materials are available and this amount may be increased by producing proved condensate reserves. New equipment will be required to produce and stabilize the desired amounts of natural gasoline but the overall new material requirement is very small when compared to that amount required to drill new wells, transport, and prepare a similar quantity and type of hydrocarbon raw material from petroleum.

In processing natural gasoline and condensate, modern methods of stabilization, isomerization, dehydrogenation, polymerization, hydrogenation, and alkylation may be employed. Fig. 5 illustrates the general processes by which natural gasoline and condensate may be used to produce the desired aviation fuel.

The value of natural gasoline blending agents now in commercial production, including *iso*pentane, is well known but with more exact specifications for super fuels, together with the current picture of critical material and crude oil, any new blending agent possessing superior blending qualities is of importance. Under these conditions the great possibilities of catalytic and thermal conversion of relatively pure light hydrocarbon fractions into base stocks and the processing of these stocks into super aviation blends must not be underestimated. As previously stated, the thermal cracking of by-product propane and ethane, in regenerative furnaces, into ethylene, propylene, and benzene is of importance. Ethylene with *iso*butane, natural, or isomerized from normal butane, has in the past produced neohexane a super blend. The future may see the same raw materials, ethylene and *iso*butane, producing super blends of still greater value. Propylene and benzene are now being alkylated to produce cumene, a super rich mixture blend, and in addition cumene may be thermally cracked to give a 50 percent yield of styrene for synthetic rubber production.

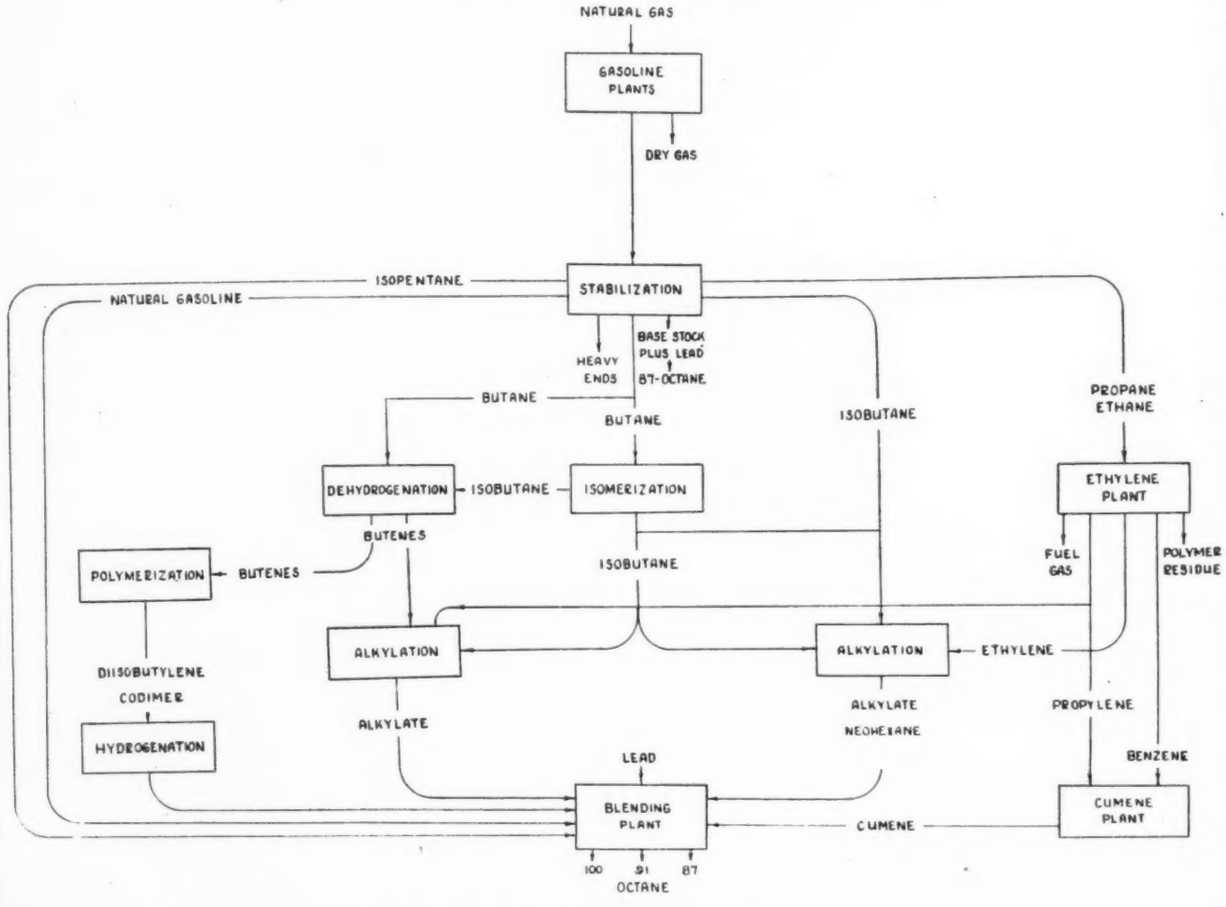
Explosives

The use of natural gas as a raw material in highly efficient processes requiring a minimum of new critical construction materials has made possible immense production of explosives. By modern methods of oxidation and cracking, natural gas may be converted in the basic raw materials from which our modern explosives may be synthesized.

The significance of ammonia in war time is very evident when Table 1 is inspected. Woodward[4] has discussed this subject in detail and lists various nitrogen compounds used in modern warfare that are derived from ammonia. The oxidation of ammonia yields nitric acid and this acid with ammonia yields ammonia nitrate. With these base mate-

[4]"Significance of Ammonia in the National Defense," E. R. Woodward, *Chemical and Metallurgical Engineering*, February, 1941.

Fig. 5. Flow sheet illustrating processes related to production of aviation gasoline from natural gasoline derivatives



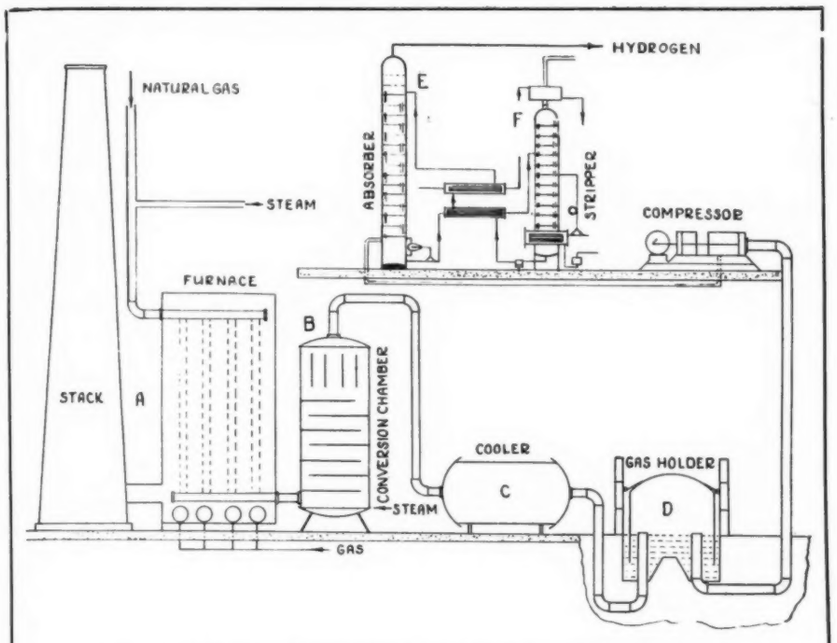


Fig. 6. Hydrogen from natural gas by the conversion process

rials explosives are prepared that are being used in great quantities for charging airplane bombs, shells, and other projectiles.

In the synthesis of ammonia, of the gases used the most expensive and difficult to obtain is hydrogen. Today approximately one-half of the emergency synthetic ammonia is prepared with hydrogen obtained from natural gas by the steam conversion process.

A general outline of the steam-conversion process[5] may be obtained by referring to Fig. 6. The initial re-forming is carried out in the furnace, (A). This radiant-type downflow furnace, gas-fired, is maintained at a temperature of 1600°F. The gas to be processed, plus steam, is passed through tubes packed with catalysts. The reaction taking place in this stage is as follows:

$$CH_4 + H_2O \longrightarrow CO + 3H_2$$

In this stage approximately atmospheric pressure is maintained in the system. The gases are then conducted to the convertor, (B), where additional steam is added and at a temperature of 850°F. with another type catalyst, the production of hydrogen is completed:

$$CO + H_2O \longrightarrow CO_2 + H_2$$

The gas is then cooled at (C), and conducted to the gas holder (D), before being compressed. The analysis of this gas, at this point in the system, is reported to be roughly 78 percent hydrogen, 20 percent carbon dioxide, and 2 percent unconverted hydrocarbons and other gases. It is extremely important that the natural gas used in this process be free of any sulphur compounds, such compounds resulting in catalyst poisoning.

The gas could be scrubbed of its carbon dioxide content at (E) and the scrubbing medium revivified at (F) should hydrogen of 97 percent purity be required. For the ammonia synthesis, however, one volume of nitrogen with three volumes of hydrogen are required and this ratio may be obtained by bubbling the hydrogen mixture through liquid nitrogen thereby supplying the desired nitrogen and attaining purification in one step.

Natural gas may be partially oxidized with air and the hydrogen-nitrogen mixture purified. This method, however, does not supply the required amount of hydrogen and must be supplemented by pure hydrogen obtained from another source.

Synthetic ammonia is not only of importance in the production of explosives, in addition it is used as a fertilizer base, rubber accelerator, and in the preparation of nitroparaffins.

The exploitation of nitrated products of aromatic hydrocarbons has resulted in the production of some of our most powerful explosives such as TNT. It is very possible that future exploitation of the nitroparaffins may produce explosives of such a nature that natural gas may develop into a still more valuable source of explosives than at present.

Benzene and toluene are valuable war products and may be produced by thermal cracking of lighter hydrocarbons; hexane and heptane fractions may also be catalytically reformed to these materials.

The raw materials required for the production of explosives, i.e., synthetic ammonia, toluene, etc., are not only of importance in war time but future peacetime needs[6] should see a steady increase in the production of these and similar type raw materials with developments in chemical processing, chief of which may be the plastic industry.

The great technologic developments in hydrocarbon chemistry have made possible the production of many war products in quality and quantity to successfully supply our armed forces. Products like silk and rubber, which cannot be obtained from their natural sources, are now being replaced by synthetic rubber, plastic goods and synthetic fibers. In addition, the rapidly expanding plastic industry supplies goods to replace critical consumer products requisitioned for war purposes. In these operations natural gas and natural gasoline supply ever-increasing quantities of hydrocarbon raw materials that are of great value in the war effort.

Conclusion

The processes stated herein, in part, represent some of many processes that are now in commercial operation or awaiting commercial development. These processes reflect a much higher field of utilization for natural gas and natural gasoline other than as a fuel and source of energy and tends to dictate that their true value will rightly be recognized by the petroleum industry in the near future. These developments offer the petroleum industry new fields and processes by which it may put to efficient use a portion of its product that heretofore has received little attention. It should be remembered that these developments have come during war time when the success of a process depends on the availability of the raw material to be processed and the efficient use of critical material required. This condition appears to suggest that the majority of these processes are economically sound and the return to peace will see them established as permanent factors in national economy. Constant vigilance on the part of the petroleum industry relative to the great potential possibilities of natural gas and natural gasoline will not only materially aid in the production of war products required by our armed forces but will place this industry in a most advantageous position to convert to the production of the immense quantities of synthetic consumer goods that will most assuredly come with the return to peace.

[5]"Hydrogenation of Petroleum," E. V. Murphee, E. L. Brown, and E. J. Gohr, *Industrial and Engineering Chemistry*, Vol. 32, September, 1940.

[6]"Useful Products From Natural Gas," F. H. Dotterweich, *Proceedings* of the Twentieth Annual Convention, Natural Gasoline Association of America, 1941.

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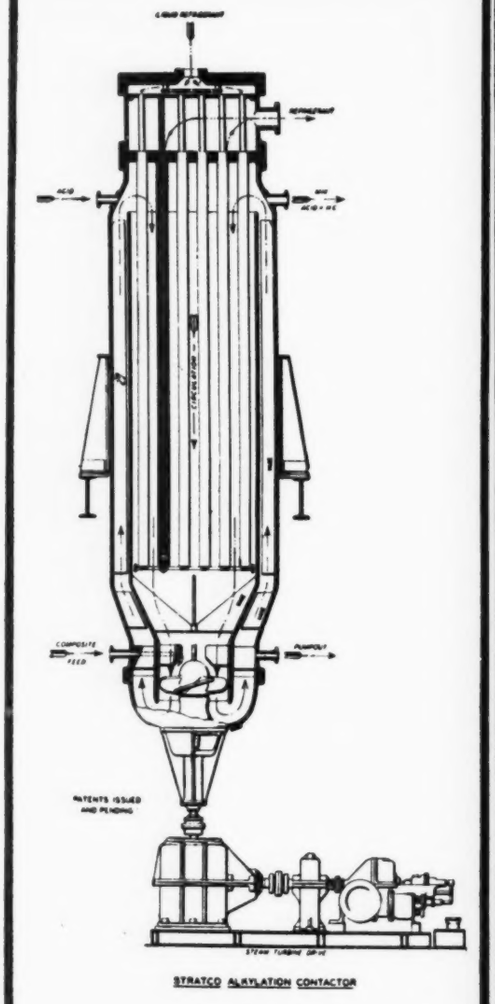

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Petroleum-Refining Methods Available for Wartime Demands*

By J. F. THORNTON and W. C. DICKERMAN, JR.
The Lummus Company

Abstract

TOTAL global war is making extraordinary demands on the oil industry. Huge quantities of 100-octane gasoline, extreme service lubes, toluene and other miscellaneous products are required. One-hundred-octane gasoline is blended from *iso*pentane, base stock, and alkylate. *Iso*pentane is fractionated from natural or refinery gasoline; but as only limited quantities of base stock can be made in this way, catalytic cracking is rapidly becoming the major source of base stock. Alkylate, the most important component, is synthesized from *iso*butane and an olefin. Extraordinary demands are forcing the full utilization of all present sources and the development of new supplies of feed stocks. Fortunately, the United States finds itself with well-developed processes already available, and this is true of the manufacture of lubricating oil as well. Toluene is now being produced by new methods from special cuts fractionated from selected crudes or from catalytically processed naphthas. Designers of refinery equipment are modifying past practices to conserve every bit of material possible.

introduction

The present world war is making severe demands upon the American petroleum industry. Not only are large quantities of high-quality fuels and lubricants required but, in addition, the petroleum industry must supply strategic commodities such as toluene for the manufacture of explosives and stocks for producing synthetic rubber. The production of these vital raw materials, which in reality are chemicals, is made possible by years of costly research and development by the petroleum industry. The vision of its leaders has resulted in the development of a petroleum technology that has expanded the oil business into a most highly developed type of chemical industry. This is one of the greatest assets of our nation in meeting wartime demands.

In considering a program of expansion for the manufacture of additional vital products, the refiner is faced with an amazing variety of processing methods. Some of the processes involved are well known and are described in the literature, others are just reaching the commercial stage and details have not been publicly disclosed. This paper will outline certain processing routes and discuss the general background involved in the selection of refining methods. Needless to say, the nature of the subject will not permit detailed discussions of refining methods, but certain generalized ideas will be presented with regard to the related engineering viewed in light of the present emergency.

*Presented before American Institute of Mining and Metallurgical Engineers, New York, New York, February, 1942.

Aviation Gasoline

Today the demand for 100-octane gasoline is tremendous. It not only increases the horsepower output of an engine of a given weight but it greatly reduces fuel consumption at cruising speed. This increased power is of paramount importance on the take-off when maximum output is required to lift a plane into the air with a large bomb load, and also it permits top performance of pursuit planes.

Through much research and development work, the industry has found that a very satisfactory 100-octane fuel is a blend of 15 to 20 percent of *iso*pentane, selected aviation base stock, and enough high-octane blending agent, such as alkylate, so that the blend will lead to 100-octane with the specified maximum quantity of ethyl fluid. The blend must also meet certain vapor pressure, distillation and other specifications.

Isopentane

The first component mentioned, *iso*pentane, used because of its convenient vapor pressure, high octane number and good lead response, is usually separated from natural or straight-run gasoline by close fractionation. In addition to these natural sources, a relatively large percentage of this hydrocarbon may be found in the gasoline from certain catalytic cracking units. *Iso*pentane is present also in thermally cracked gasoline, and this material can be recovered if required. In addition to these many sources of *iso*pentane, it is possible to isomerize normal pentane, but as yet it has not been necessary to resort to this method. As only moderate amounts of *iso*pentane are used in aviation gasoline, the overall available supply is adequate, although additional facilities are required in some cases in order to achieve maximum recovery.

Base Stock

The so-called base stock used for blending aviation gasoline is the component that until recently has not received a great deal of attention in the way of special processing methods. The base stock must be a material of good octane rating and high lead response. Furthermore, due to the extreme storage conditions to which aviation gasoline is sometimes subjected, straight-run stock and certain special catalytically produced gasolines are preferred because of oxidation stability and low gum-forming characteristics. In the early stages of production of aviation gasoline, selected straight-run gasolines were used exclusively as base stock, but unfortunately most crudes do not yield a gasoline of good octane rating for the required boiling range fraction.

Now that large volumes of aviation gasoline are required, there arises the problem of producing increased quantities of high-quality base stock. In view of the limited supply of naturally occurring base stock of suitable quality, attention is directed to alternate methods of obtaining this material. One means of increasing the volume of high-quality base stock available is precise fractionation of low-octane straight-run gasoline. Essentially, this process amounts to the separation by boiling point of narrow-range high-octane cuts containing chiefly *iso*paraffins, which are blended to yield a superior base stock. Alternately this operation may be considered as the removal of low-octane normal paraffins. The commercial application of this type of distillation is already a reality and the process can be used for improving stocks from the large majority of available crudes. One advantage of this method is that the equipment, although often large in size and requiring considerable fuel, is essentially of simple design and construction, and requires no complex machinery. The method, therefore, eases the demands on the machinery and allied industries, permitting its application to varied locations, to utilize naturally occurring materials to the best advantage.

The rapid development of catalytic cracking in the last few years has resulted in making available to the refiner special catalytically produced gasoline that is exceptionally good base stock. A recently announced development for the improvement of base-stock quality is catalytic naphtha isomerization, which converts normal paraffin hydrocarbons of comparatively low octane into isomers of higher octane rating.

The desulphurization of base stocks for the purpose of improving lead susceptibility offers in many cases a relatively inexpensive method of increasing production of aviation gasoline. In one instance it is reported that a base stock containing 0.057 percent sulphur was subjected to catalytic desulphurization,

reducing the sulphur content to 0.013 percent and, owing to improved susceptibility, a 32 percent increase in production of 100-octane gasoline was indicated. In another case a base stock containing only 0.009 percent sulphur was processed to 0.0009 percent sulphur content and the increased lead response indicated 10 percent additional production of aviation gasoline. The order of these figures is such that the importance of desulphurized stock is evident.

Consideration of the many practical methods of producing base stocks of high octane rating and good lead response will indicate the economic advantages of increasing production of aviation gasoline by the proper preparation of base stocks.

Alkylate

The most important component of 100-octane gasoline is the high-octane blending agent. There are several ways of producing a satisfactory material for this purpose but alkylation is the most widely used process at the present time. For many years it has been known that the highly branched *iso*paraffins of eight or so carbon atoms have the combined advantages of high octane number and good lead response, so considerable work has been done to develop processes for producing material of this type. Selective polymerization of butylenes and subsequent hydrogenation was probably the first commercially used method. Thermal alkylation to produce neo-hexane, an exceptional blending agent, is another commercially used process. The recent development of catalytic alkylation has been one of the most important advances in the petroleum industry and has permitted widespread commercial production of blending agent at relatively low cost. Discussion here will be limited to a consideration of alkylate as the chief component of 100-octane gasoline.

The word alkylation is commonly interpreted to mean the catalytic junction of an *iso*paraffin with an olefin hydrocarbon. Sulphuric acid has been and still is the most widely used catalyst, but another that is now being used commercially possesses important advantages. *Iso*butane is the most commonly used *iso*paraffin; there are no lower-boiling *iso*paraffins, and *iso*pentane, the next heavier homologue, is incorporated directly in aviation gasoline blends.

Among the numerous olefins that will alkylate, the butylenes are preferred, although it is possible to alkylate propylene, amylene and even highly olefinic low-boiling gasoline. In general, *iso*butane and butylene give the product with the highest octane number and consume the least catalyst, which makes them of greatest commercial importance.

*Iso*butane is found widely in nature and is commercially recovered in natural gasoline plants and fractionated from straight-run gasoline. It is also found in almost all cracking-plant streams in varying concentration. Before the demand for aviation gasoline was increased by war emergencies, with resulting emphasis on alkylation, *iso*butane was considered a waste product in the same sense as propane. No one with proper equipment tolerated much of it in motor gasoline because it could be replaced by about half again its volume of normal butane. Now the picture is changed and all available *iso*butane must be recovered and converted into alkylate. This means that some of the equipment available in the gas fields and in refineries should be redesigned for high recoveries. Most refinery sources at the present time are comparatively well utilized but much remains to be done in the natural gasoline plants scattered over the nation. The demands are so great that this naturally available supply will prove inadequate. Fortunately, there are available, and already in commercial operation, isomerization processes that will convert normal butane, available in larger quantities, into *iso*butane with very little loss. More *iso*butane is available from catalytic cracking units and additional units of this type now under construction will add to the supply.

The four isomeric forms of butylene, which are highly reactive chemically, are never found in crude oils. Recently special units have been installed to increase the production of butylenes, but heretofore their sole source has been as a side product of cracking. It is for this reason that almost all alkylation units to date have been installed in refineries that have olefins available. It is evident, however, that the demand for alkylate may exceed that obtainable from the present supply of olefins in refineries. Polyform, gas reversion and similar type units can be used to produce large volumes of butylene from naphtha and butane. Some increase can be secured by refinements in operating conditions and modifications to existing cracking units, including deep reforming, but ultimately units designed especially for the dehydrogenation of normal butane into butylenes may be required. Undoubtedly this will be done catalytically, because in this way undesirable side reactions, which reduce ultimate yields, are suppressed.

To summarize, the increased demand for alkylate necessitates: (1) the revamping of existing gasoline plants to give the largest possible recovery of *iso*butane and further supplementing this supply with *iso*butane from isomerization units, thermal cracking units and catalytic cracking units; (2) butylene production will be increased by various cracking operations and catalytic dehydrogenation. The increased usage of butanes and butylene for producing alkylate, and also the usage of these hydrocarbons in connection with butadiene production, will result in there being very much less butane and butylene available for sale as bottled gas or for incorporation in motor gasoline. Propane may come into general use to meet requirements of vapor pressure of motor gasoline.

The design and construction of alkylation plants involves none but routine technical problems. The commercially used catalysts are noncorrosive and, practically speaking, no alloys are required. There are no extreme conditions of temperature and pressure and no special equipment is necessary other than that ordinarily found in refineries. The industry is fortunate in having several years of commercial operating experience behind it at the present time to point the way to operating and design refinement that are reducing the cost and increasing the yield and quality of the alkylate now being manufactured.

Although several commercial isomerization plants are in operation, there is still much work being done along this line. The catalytic dehydrogenation of normal paraffins has been studied for many years in various petroleum research laboratories and so the rapid commercial development of this process can be expected.

Lubricating Oils

The demands for lubricating oils fall roughly into two categories; regular quality lubes in common civilian use and high-quality lubes required for planes and Diesel engines. The former is available in large volumes and is satisfactory for the requirements of army land vehicles propelled by automobile-type motors. On the other hand, the increased numbers of airplanes, airplane-engine-powered tanks and Diesel-powered craft on land and sea has increased tremendously the demand for extreme service lubes, the quantity production of which represents another problem for the petroleum industry.

The production of the highest quality lubes requires the application of solvent refining and dewaxing processes, which, fortunately have already attained a high degree of perfection in commercial practice. The expansion of these facilities introduces few technological problems.

Careful consideration is being given to the maximum utilization of the many existing modern lubricating-oil manufacturing plants, particularly by

selection of charging stocks. The utilization of these modern lube-oil facilities for the production of larger volumes of high-viscosity aviation lubes would ultimately result in a lowering of the quality of available automotive lubricating oils. To simplify the number of product specifications and handling problems, probably it will be desirable to maintain present quality standards for the bulk of the output of automotive motor oil, in order to have an ample and easily obtainable supply of lubricants for military trucks and other vehicles. The required expansion of manufacturing facilities to carry out this plan involves relatively small amounts of material and very few technical problems. The use of additives to improve certain properties of lubricants has been well developed by the industry and until recently these materials have been available in generous quantities.

The country should consider itself extremely fortunate with regard to its supply of lubricating oil. This is in sharp contrast to the Axis nations, which have no supply of high-quality lubricating-oil crudes and reportedly have not been able to meet their requirements by synthetic methods.

Toluene

The technology of the production of toluene from petroleum is now developed to a point where the petroleum industry is in a position to produce virtually unlimited quantities of this strategic raw material at reasonable costs. Most crude oils contain some toluene and the segregation of this material has received considerable attention. Generally speaking, the average crude oil in the United States contains very little toluene and the isolation of this material from crude sources is economically restricted to certain selected crudes.

By special catalytic reforming of naphthas, a product extremely high in toluene content can be obtained. This general scheme of operation is one of the economical methods of producing large volumes of toluene as a unit operation. Most thermal reforming operations, especially the polyform and gas-revision types, yield gasoline that contains appreciable quantities of toluene, the exact amount depending upon the operating conditions and yields. The selection of the particular process to be used in any refinery for the production of a toluene-rich stock involves consideration of the interrelation between toluene production and motor-fuel production. The removal of toluene from high-octane aromatic-type gasoline reduces slightly the octane number of the residual motor fuel, and it is preferable in some cases to operate units exclusively for producing toluene.

The purification of toluene as a raw concentrate or as finished nitration grade is essentially the same problem, regardless of whether this compound is being isolated from straight-run naphthas or from synthetic stocks. The first step is to concentrate the toluene in a narrow boiling fraction, which is then usually subjected to a special distillation process to isolate the aromatic compounds present. The raw toluene thus produced is given a simple finishing treatment and then is satisfactory for nitration purposes. Various other schemes for isolating toluene from concentrates can be used, but, in general terms, the final concentration can be achieved by the application of well-established processing methods.

The units required for the concentration of toluene are relatively simple and do not involve any special equipment. The major investment is in standard equipment and should the demand for toluene be greatly reduced, this equipment could, no doubt, be salvaged and put to use in other services. Likewise, with minor modifications, the processes that would be used for the production of synthetic toluene-bearing stocks can serve for the production of motor fuel if the demand for toluene is greatly reduced.

Other Special Products

The petroleum industry also has been called on to produce various chemicals and, in particular, raw material for manufacture of synthetic rubber. Quantities of butadiene will be required and this material can be produced by thermal or catalytic dehydrogenation of butane or other stocks. Discussion of this subject is beyond the scope of this paper,[1] but it should be noted in passing that here again the high state of development of petroleum research makes possible this valuable contribution to the war effort.

General

The engineering economics of petroleum-refining processes must be viewed in light of the present emergency demands. Basically today's problem is to get the maximum production of vital products in the shortest time with the minimum requirements of steel and machine-hours. This thought necessarily influences every decision on refining methods. Several general thoughts regarding the production of aviation gasoline should be stressed. The maximum utilization of available *iso*pentane, butanes and butylenes is of primary economic importance, and utilization of other available olefinic feed stocks for alkylation should be studied carefully. The advantages of producing high-quality base stocks were pointed out in preceding paragraphs, and this means of increasing 100-octane gasoline production will prove economical in many cases. The production of increased quantities of lubricating oil, toluene and other special products, while involving smaller volumes, must also be viewed in light of achieving the desired capacity with minimum delay and minimum material requirements.

The engineering of refinery projects involved in the wartime program is being carried out so as to minimize the demands on engineering facilities and on the material suppliers. First, due consideration must be given to the use of available designs and, in the ideal instance, new plants should be duplicates of plants already designed in order to save time. This is important because the large volume of refinery construction work has resulted in a sharp increase in activity in this field and drafting capacity is at a premium.

Many special company standards are being waived when their use will result in delays and this factor will also make more likely the possibility of utilizing duplicate designs as mentioned above. The use of alloys should not be considered in the usual light of long-time replacement payout. Large vessels in corrosive service probably should be lined because of the difficulty of replacement, but easily replaceable piping, furnace tubes, etc., could be of carbon steel if this material will last several years with safety. This will relieve the demand on the alloy-steel industry and will permit the more rapid delivery of the refining unit involved. Many specifications call for steel-framed fireproofed structures, and, in order to decrease steel requirements, designs are being altered to utilize reinforced concrete in many cases.

In certain instances it may be advisable to incorporate into units with large heat loads facilities for waste-heat steam generation. The installation of such a relatively simple generating system may obviate the necessity of boiler-plant expansion and increased steam production can be obtained with the minimum steel requirement.

Another angle that is important is that all special trimmings on refining units are being eliminated. In many places it is possible to reduce the amount of steel used without reducing the safety factor or increasing maintenance problems. If refrigeration systems are required, the use of readily available propane as a refrigerant can be considered. The use of modern absorption-type refrigeration units may be desirable if compressor deliveries are long. These are but typical of the many engineering ideas that are being considered to relieve the demands refinery construction places on certain other already heavily loaded industries.

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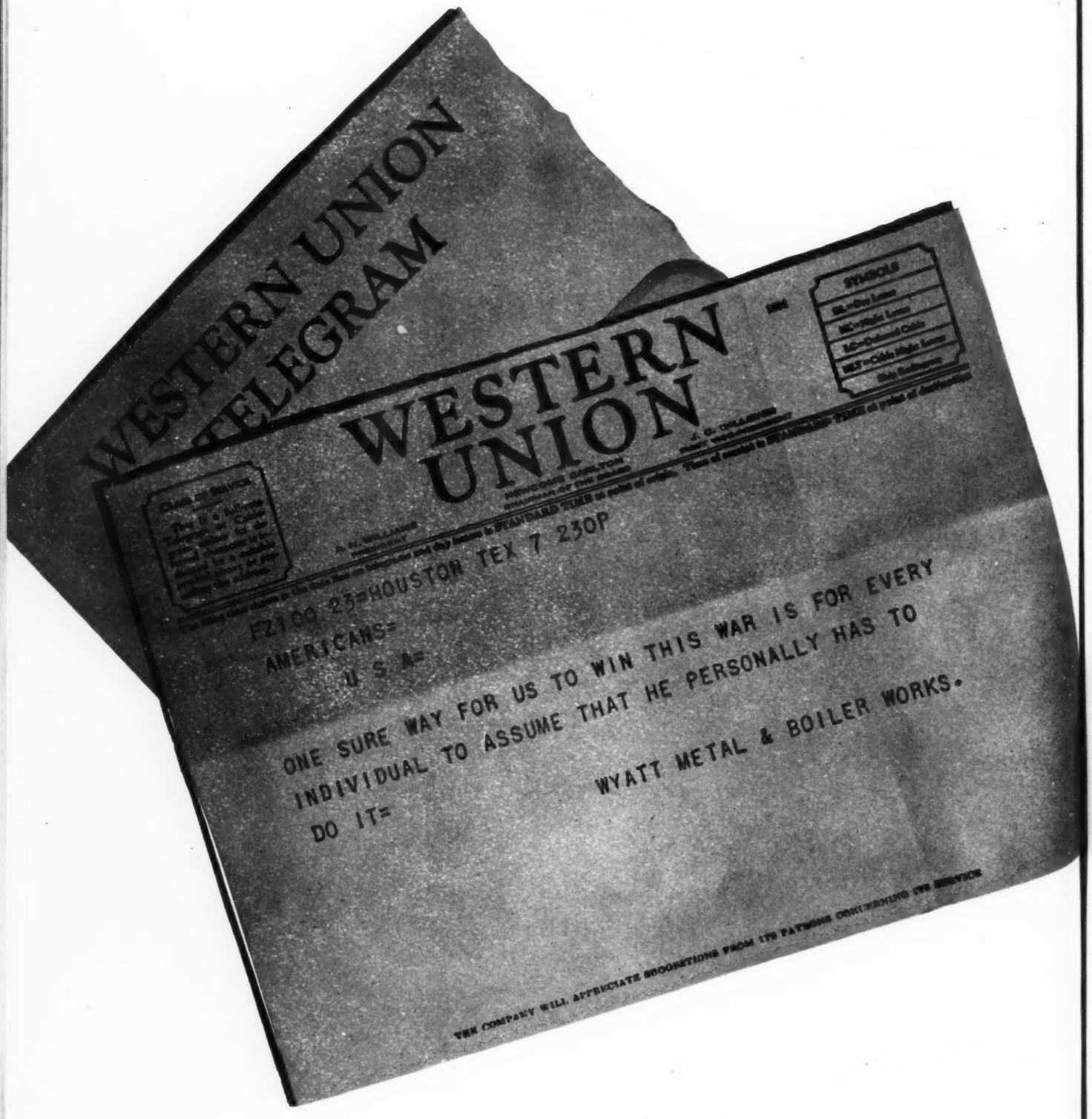
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The Thermofor Catalytic Cracking Process*

By T. P. SIMPSON, L. P. EVANS, C. V. HORNBERG, and J. W. PAYNE

Socony-Vacuum Oil Company, Inc.

Abstract

THE Thermofor catalytic cracking (TCC) process is one of the major new developments in the art of catalytic cracking. The process development has been carried through the semi-commercial stage in a 500-bbl.-per-day plant to the present design of commercial units ranging in oil-charging capacity from 2,500 bbl. to 10,000 bbl. per day. The process operates on the principle of continuous catalyst flow through the reaction zone, with the catalyst circulating continuously through separate systems, which form a complete cycle of cracking and revivification. The separate reactor and regenerator units are designed for efficient utilization of cheap catalysts and for flexibility of operation.

The TCC process is inherently suitable for both catalytic cracking and catalytic vapor-phase treating. Although developed, prior to the war, for cracking to produce high-octane motor gasoline, the process is equally adaptable, both in the present emergency and in the post-war period, to the production of high-octane aviation gasoline. In addition to gasoline, the process yields substantial quantities of other valuable products such as the butane-butylene fraction for alkylation-plant charge, C_5 hydrocarbons, aromatics, and heating oils.

Important features of the plant design may be summarized as: low construction and operating cost, extensive use of conventional refinery equipment, low requirements of strategic materials, the use of low-pressure blowers instead of compressors for supplying the regeneration air, conversion of regeneration heat to high-pressure steam, and adaptability to small- as well as large-scale refineries. This paper presents a general description of the TCC process and its relation to other existing commercial catalytic cracking processes, viz., the Houdry and fluid catalyst processes.

Introduction

Commercial catalytic cracking of petroleum as practiced today is a comparatively recent development. It has only been during the last decade that this type of processing has attracted the widespread interest of the petroleum refining industry. Now due to the great importance of catalytic cracking in the production of such important war materials as aviation gasoline, butane-butylene hydrocarbons, aromatic hydrocarbons, and butadiene, the commercial application of catalytic cracking has received an enormous impetus as a result of the war effort.

Starting about 1927 Eugene Houdry was one of the pioneers in this field, and as a result of his early investigations gained strong backing by Socony-Vacuum Oil Company, Inc., and the Sun Oil Company. This group, working together through their respective research, development, and engineering organizations, attained notable success in developing catalytic cracking to the commercial stage. The first commercial Houdry catalytic cracking units were placed in operation in 1936; and since that time the Houdry[1] process has been accepted widely, and is used in the petroleum industry for producing motor fuels, aviation gasoline, and numerous allied products. The advantages of catalytic cracking were recognized quickly by the petroleum industry; and, as a result of further intensive development work, particularly during the last five years, new types of processes have attained commercial status.

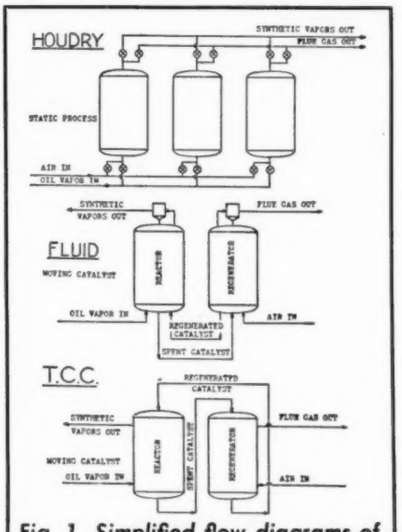


Fig. 1. Simplified flow diagrams of Houdry, Fluid, and TCC processes

Present Processes

At the present time the major catalytic cracking processes and interests may be listed as shown at the bottom of the page.

By the end of 1943, it is estimated that these processes will have an installed charging capacity to the catalytic reactors of approximately a million barrels per day. The Thermofor catalytic cracking process—commonly referred to as the TCC process—represents one of the modern developments in this field. It is the purpose of this paper to acquaint the petroleum industry with the TCC process, describe some of its salient features, and to point out its relationship to the above-mentioned contemporary processes. Before proceeding with a detailed discussion of the TCC process, however, it will be interesting to describe how Houdry, fluid, and TCC fit into the broad technical field of catalytic cracking.

Basic Types

Catalytic cracking reactions may be classified broadly according to the physical state of both the catalyst and the reacting hydrocarbons in the reaction zone. The hydrocarbons may be reacted in either the vapor or liquid phase, whereas the material acting as a catalyst may be a solid, liquid, or vapor. In the commercially important processes for catalytic cracking hydrocarbons are substantially vaporized and cracked in the presence of solid catalysts.

Many types of catalysts have been developed for use in these three processes, but at the present time contact- or adsorptive-type materials—comprising chiefly silica-alumina compositions, made by synthesis or by the chemical treating of natural clays—are used al-

*Presented before American Petroleum Institute, Annual Meeting, Chicago, Illinois, November 9-13, 1942.

Name	*Type*	*Principal development organizations*	*Licensors or licensing agents*
Houdry	Static catalyst	Houdry, Sun Oil Company, Socony-Vacuum Oil Company, Inc.	Houdry Process Corporation; E. B. Badger and Sons Company, The Lummus Company, Bechtel-McCone-Parsons.
Fluid	Moving catalyst	Standard Oil Company (New Jersey) and subsidiaries; Standard Oil Company of Indiana; M. W. Kellogg Company; The Texas Company; Universal Oil Products Company, and Shell Oil Company, Inc.	M. W. Kellogg Company, Universal Oil Products Company.
Thermofor	Moving catalyst	Socony-Vacuum Oil Company, Inc.	Houdry Process Corporation; E. B. Badger and Sons Company, The Lummus Company.

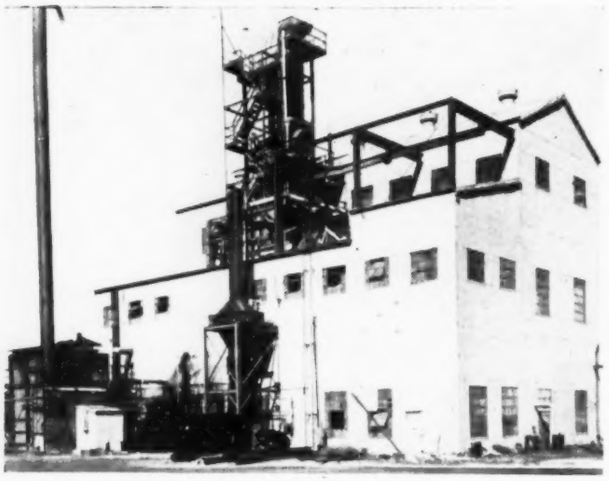


Fig. 2. General view of semi-commercial TCC development unit

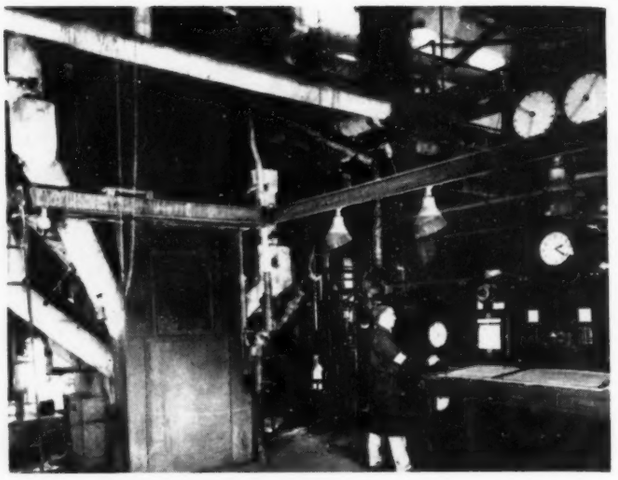


Fig. 3. View of base of TCC development unit, showing control panel

most exclusively for this purpose. In this paper these types of materials will be assumed as the catalysts under consideration, and they may be referred to as either "synthetic" or "clay" catalysts. Catalysts of this type are used commonly in the form of granules, powders, or pellets ranging in particle size from about one-quarter inch to a few microns.

Cracking processes employing solid-type catalysts may be divided further into two basic types, according to the method of applying the catalyst:

1. Reaction systems, in which the catalyst contact mass remains static in the reaction zone and the vapors pass over the fixed catalyst bed: Houdry units exemplify this type.

2. Systems in which the catalyst moves continuously through the reaction zone: TCC and fluid units are in this class.

Simplified flow diagrams of these types of operation are shown in Fig. 1.

Both the static- and moving-bed systems are designed commercially to provide continuity in the flow of oil to the cracking plant; and in this respect the Houdry, as well as the TCC and fluid operations can be classed as "continuous" processes. However, technical men view the differences in the manner of handling the catalyst as the most significant distinguishing characteristic of these processes, and for this reason generally have accepted the terminology that calls the fixed-bed type (Houdry) "static" processes, and the moving-bed type (TCC and fluid) "continuous" processes. This terminology is used in this sense hereafter in this paper.

Common Characteristics

Because the TCC, Houdry, and fluid processes employ the same fundamental type of cracking reaction, they have several characteristics in common. For example, in all three types of units exposure of catalyst to oil vapors under cracking conditions fouls the catalyst with a carbonaceous deposit (commonly referred to as "coke"), which greatly reduces the catalyst activity and requires removal to restore the catalyst to its proper level of activity. This deposit is removed from the catalyst by combustion with air. On the basis of commercial units with a capacity of 10,000 bbl. per day, the amount of coke burned may vary from 20 to 120 tons per day, depending on the type of operation being conducted. Continued use of the catalyst at high temperatures causes it slowly to lose activity, and replacement of the catalyst is required either continuously or periodically. The performance of the processes is dependent, to an important extent, on the amount of catalyst used relative to oil, activity of the catalyst, soaking time, temperature, and pressure.

Having these basic features in common, the differences between TCC, Houdry, and fluid processes lie chiefly in the physical methods employed in handling the catalyst, in contacting the oil and catalyst, and in regenerating the catalyst. Commercial units reflect the ingenuity of development engineers who have arrived at three distinct practical schemes for performing these operations, all of which are fundamentally sound.

Before proceeding with a detailed description of the TCC process, a brief summary of the Houdry and fluid operating principles is presented for comparison. In view of the fact that the product-distillation and feed-preparation equipment used in all catalytic cracking plants are of rather conventional type, the following discussion will be limited to the catalytic cracking and regeneration systems proper. It is assumed throughout this discussion that the charge to the catalytic reactor is delivered at proper temperature and pressure, and that the synthetic crude from the reactor will pass to a suitable distillation and stabilizing plant for the preparation of products and recycle stock.

Houdry—Static Units

Houdry units comprise three or more catalyst-containing vessels, called "cases," manifolded together by suitable piping and valving so that one or more of the cases may be on stream while the remainder are being regenerated. The vapors and air streams are switched from case to case by a precisely synchronized valve timing system. A complete typical cycle for a given case in a 3-case unit involves 10 min. on stream, 10 min. valving and purging, and 10 min. burning. By staggering the operation of the cases so that one case is always on stream, the flow of oil is maintained continuously through the system. Units having a charging capacity of 10,000 bbl. per day usually have 4 or more cases, whereas larger units may employ 12 cases. The catalyst in the cases remains as a fixed bed ("static"); and, as the cases alternate between burning and on-stream operations, it is necessary to provide a heat-transfer system in the cases to maintain the catalyst temperature at proper levels. This is accomplished by circulating a heat-transfer medium, usually molten salt, through finned heat-transfer tubes extending through the catalyst mass. By maintaining the heat-transfer medium at proper temperatures, normally 800 to 900°F., the catalyst is prevented from attaining heat-damaging temperatures while it is being regenerated. The

catalyst is usually in the form of pills or pellets approximately 1/6 in. in diameter and length. Both clay and synthetic catalysts are employed.

Fluid—Moving-Bed Units

The fluid process employs separate reactor and regenerator units, through which the catalyst circulates continuously, undergoing alternate reaction and regeneration. The reactor operates continuously on cracking, with the oil and catalyst streams entering and leaving at fixed points. The regenerator operates as a burning unit, with air and catalyst streams likewise entering and leaving continuously at fixed points. The catalyst employed is in the form of a powder ranging in particle size from about 300-mesh down to a few microns. In the reaction system the powder catalyst is mixed intimately with oil vapor, and this mixture flows through an enlarged reaction zone. On leaving the reactor, the spent catalyst first is separated from the vapor in cyclone separators, and then transferred to the regenerator. The operation of the regenerator is similar to that of the reactor, except that the catalyst is carried by the air and flue-gas streams. Cottrell-type precipitators are employed to recover fine catalyst particles not recovered in the cyclone separators. Although details of the process have not been published, the foregoing is apparent from the patent literature.

TCC—Development

The TCC process derives its name from the Thermofor type of clay-burning kiln that is employed as the catalyst regenerating unit. The Thermofor kiln* and the TCC process both were developed by engineers of the Research and Development Division of Socony-Vacuum Oil Company, Inc. The first commercial installation of the Thermofor kiln for percolation clay burning was placed in operation early in 1939, and since that time 5 additional units have been installed and operated for that purpose. These units have given excellent performance in service as clay burners. Prior to the time the Thermofor kiln reached the commercial scale, work on continuous catalytic cracking embodying the broader principles of the TCC process already had been well advanced, and the need for an efficient catalyst regenerating unit had been appreciated fully. In view of this need, the adaptation of Thermofor kilns to TCC service offered a logical and attractive course to follow, and started the commercial development of the TCC process to a fully integrated continuous catalytic cracking operation.

The large-scale development work on TCC has been conducted in a semi-commercial unit having a reactor charge capacity of 400 bbl. to 500 bbl. (42. gal.) per day. This unit (see Figs. 2 and 3) has been operated for almost two years for a study of the variables of the process and for the development of improvements in equipment. The design of numerous commercial units now under construction is based on developments proved in this equipment, supplemented by extensive fundamental laboratory studies.

TCC—Type of Catalyst

In adapting the Thermofor kiln to cracking-plant service, it was necessary to provide a catalyst having flow characteristics similar to the granular percolation clays. Catalysts of this type have been developed successfully in the form of granular masses consisting predominantly of particles varying in coarseness from about 4- to 60-mesh size. In this form, the catalyst mass flows freely through properly designed equipment. Catalysts may be formed to the proper particle size by the pelleting or extruding of powdered materials, or by the crushing of large lumps.

Satisfactory catalysts must possess proper catalytic activity and at the same time be sufficiently rugged to resist mechanical breakdown in the cracking plant. The useful life of a catalyst in service is governed both by its physical strength and its catalytic stability. At present commercial catalysts used in the TCC process are prepared from especially treated natural clays which are cheap, costing only a few cents per pound, and available in large quantities. Attrition rates for these catalysts in commercial TCC units will be less than one pound of catalyst per barrel of total oil charge to the reactor. Other catalysts of the synthetic or semi-synthetic type show considerable promise for future use.

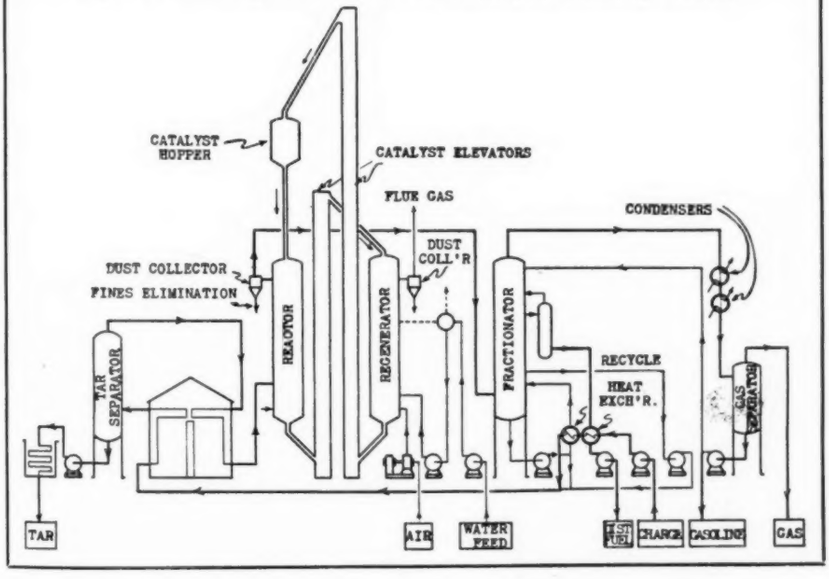
Flow in TCC Units

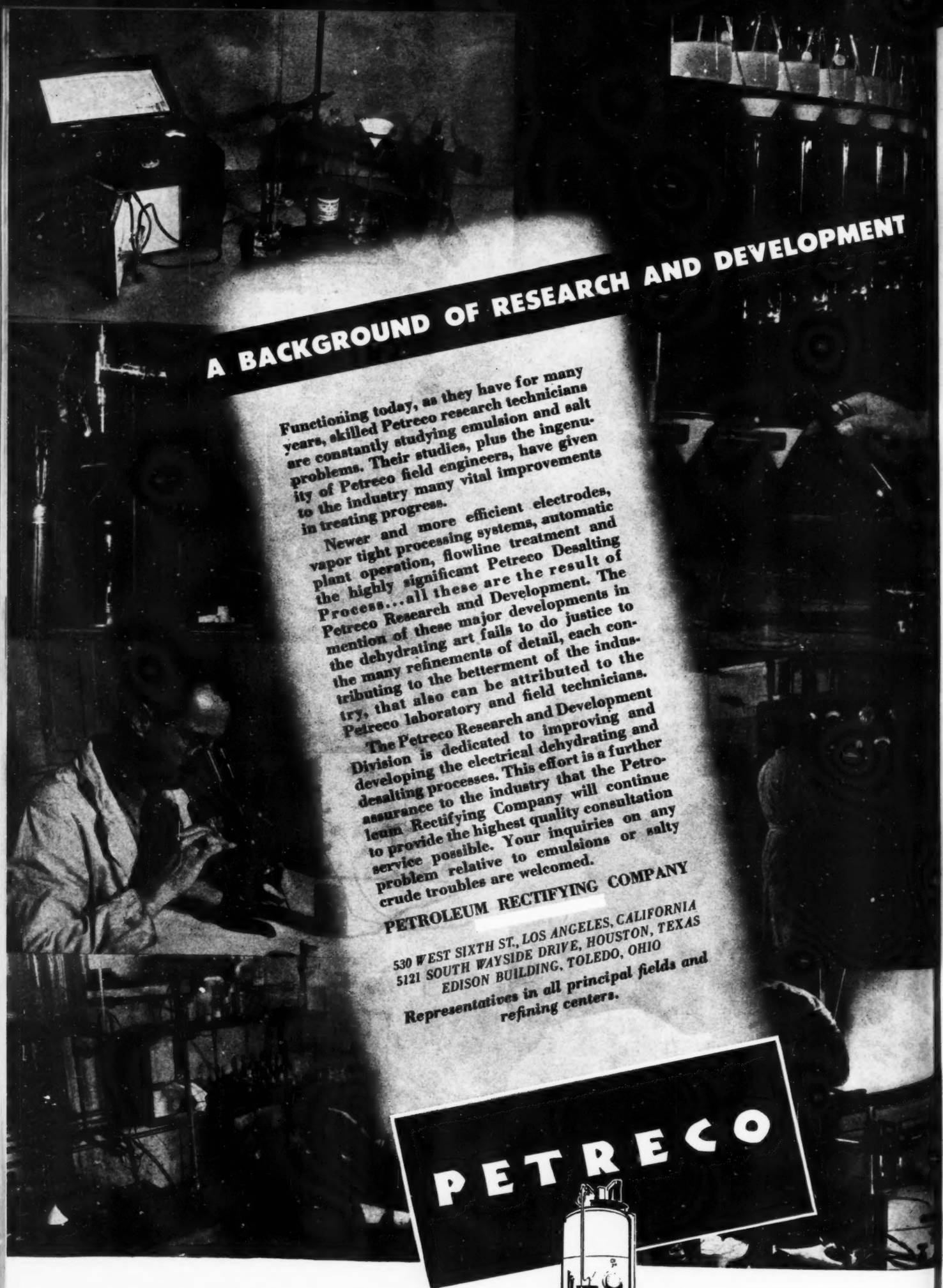
Referring to the simplified TCC flow diagram (Fig. 4), it will be noted that the catalytic part of a TCC plant comprises separate reactor and regenerating systems through which the catalyst is circulated continuously. In this respect the TCC and fluid processes may be regarded as similar; but the similarity ends here, because the two processes differ widely in principle of operation. This will be apparent from the following detailed description of flow in a TCC plant.

Starting with the catalyst hopper (Fig. 4) situated directly above the reactor, the clay flows downward by gravity through an elongated clay feed pipe, which supplies catalyst to a distributing hopper immediately above the reaction zone. Catalyst flows from this distributing hopper through several distributing pipes to the top of the main catalyst bed in the reactor. From this point the catalyst gravitates downward through the reactor countercurrent to the oil vapors, which enter at the bottom of the reaction zone. The reaction zone contains iron baffles designed to provide intimate contact between the vapors and catalyst, without interference with the uniform flow of the catalyst. At the top of the reaction bed, vapors are released from the catalyst mass, in which mass are contained several flues that collect the vapors from

*The Thermofor kiln is licensed for regenerating petroleum decolorizing absorbents by the Max B. Miller Company, 501 Fifth Avenue, New York, under patent rights owned by Socony-Vacuum Oil Company, Inc.

Fig. 4. Flow diagram of Thermofor Catalytic Cracking Process





A BACKGROUND OF RESEARCH AND DEVELOPMENT

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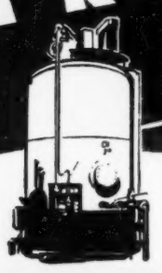

DEHYDRATING **DESALTING**

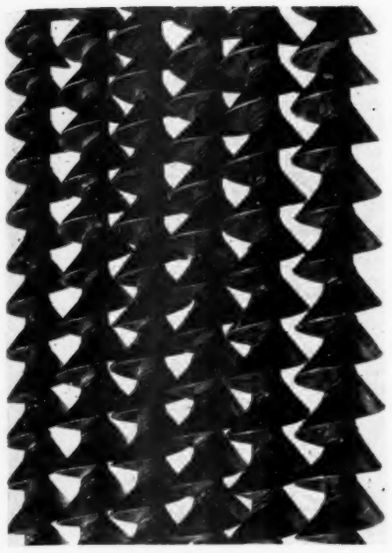

Fig. 5. Helical-tube elements of the spiral-fin type of Thermofor kiln

the reaction zone proper and conduct them through the top part of the catalyst bed into the open space immediately above. Below the oil inlet there is a purge zone, likewise containing baffles, in which the spent catalyst leaving the reaction zone is purged of oil vapors by means of superheated steam. After having been purged with steam in the bottom of the reactor, the spent but purged catalyst is released through a valve and flows into a conveyor, where it is carried to the supply hopper of the Thermofor-type kiln used for regenerating the spent catalyst.

From the kiln supply hopper, the spent catalyst flows through distributor pipes to the top of the catalyst bed in the kiln burning zone. It then passes downward by gravity flow through the burning zone of the kiln countercurrent to the air supplied for burning. In this zone the carbonaceous deposit is removed from the catalyst by combustion with air. A number of special types of TCC kilns have been developed for catalyst regeneration, but for practical purposes the spiral-finned type of Thermofor kiln[2] may be considered as representative. With this type, the main burning zone of the kiln is filled with a bundle of spiral-finned tubes. Tubes of this type are illustrated in Figs. 5 and 6. These tubes are designed to provide air passages up under the spiral fins, while catalyst moves slowly downward over and around the fins. Molten salt, steam, or other heat-transfer mediums may be circulated through the finned tubes to control burning, and to prevent the catalyst from attaining heat-damaging temperatures. The fins provide both air passages and heat-transfer surface. Air required for burning is supplied near the bottom of the finned tubes. Combustion gases are released from the catalyst mass by means of flues, which flues pass through the clay bed immediately above the heat-transfer system. Regenerated catalyst leaving the bottom of the kiln passes through a valve, and is picked up by a second conveyor which discharges it into the catalyst hopper above the reactor, thus completing the circuit. Catalyst flow rates through the reactor and kiln are controlled by adjusting the valves on the lines discharging catalyst from the bottom of these reactor and kiln units to the conveyors. It will be noted that regeneration of the catalyst is controlled without the recycling of flue gas or catalyst in the regeneration system.

The range of operating conditions for reactor and kiln in the TCC process is as follows:

Reactor	
Temperature in reaction zone, °F.	750 to 950
Reactor pressure, lb. per sq. in.	10 to 15
*Space velocity	0.2 to 3.0
†Ratio of catalyst to oil	1.0 to 8.0
Steam, percent by weight of oil charge	0 to 20
Regenerator	
Regenerator temperature, °F.	700 to 1100
Operating pressure	Atmospheric
Air consumption, standard cubic feet per ton of catalyst circulated	2000 to 20,000
Temperature of air supply, °F.	Atmospheric to 1000

*Space velocity is calculated as the ratio of volume of liquid oil charge per hour to apparent volume of catalyst mass in reaction zone.

†Ratio of apparent volume of catalyst circulated to liquid volume of oil charged per unit of time.

It will be noted that the TCC process requires only moderate temperatures and pressures, which may be attributed largely to the efficient method of reacting and revivifying the catalyst. This has been translated into a plant design that is both economical and flexible. Thus, plant construction is inexpensive, involving chiefly carbon steel and conventional refinery equipment. The process requires no compressors, the combustion air to the kiln being supplied by a low-pressure blower. The kiln itself has a variable regeneration capacity, permitting a wide choice of cracking conditions and charging stocks; and also is designed to convert the excess heat obtained from catalyst regeneration into high-pressure steam. Finally, plants can be designed in smaller sizes without serious sacrifice in economy, thus making the process attractive to small- as well as large-scale operators. At present TCC units have been designed in sizes of 2,500 bbl., 5,000 bbl., and 10,000 bbl. of charge per day to the reactor, but intermediate sizes may be designed to meet any requirement.

The high degree of flexibility of the TCC process is demonstrated by the

TABLE 1

Typical yields obtained by TCC cracking of Mid-Continent gas oil for motor gasoline

	Case "A" single-pass operation	Case "B" 1-to-1 recycle operation
Temperature, °F	850	860
Pressure, lb. per sq. in. gauge	10	10
Yields on fresh feed (percent by volume):		
Motor gasoline, C_4-free	39	56
Catalytic gas oil	48	26
*n*Butane	3	2
*Iso*butane	4	5
*n*Butylenes	5	6
*Iso*butylene	1	2
Total liquid products	100	97
Fuel gas, C_3 and lighter (percent by weight)	5	9

TABLE 2

Properties of typical motor gasolines from TCC cracking on clay catalyst

Source °F gasoline	Paraffinic gas oil	Mixed-base gas oil	Naphthenic gas oil
Gravity, of A.P.I.	60.6	60.0	52.7
Reid vapor pressure, lb.	9.6	9.7	9.5
Doctor test	Negative	Negative	Negative
Mercaptan test	Negative	Negative	Negative
Copper-dish gum, mg.	16	27	10
Glass-dish gum, mg.	1	2	2
Oxygen-bomb test, hours and minutes	12:30	20:30	8:30
Color, Saybolt	+16	+10	+15
Octane No.			
CFR motor method (without TEL* addition)	76.9	78.1	82.0
CFR research method:			
Without addition of TEL	84.1	87.4	92.0
With addition of 1 ml. TEL per gal.	91.9	93.1	96.5
With addition of 2 ml. TEL per gal.	93.7	94.8	98.2
With addition of 3 ml. TEL per gal.	95.1	96.0	99.2
A.S.T.M. distillation (°F.)			
Initial boiling point	90	89	88
5 percent point	110	106	110
10 percent point	121	119	125
20 percent point	145	140	156
30 percent point	175	170	198
40 percent point	209	206	237
50 percent point	243	240	267
60 percent point	276	268	294
70 percent point	307	301	322
80 percent point	337	332	346
90 percent point	376	365	369
Endpoint	404	398	410
Recovery, percent	97.5	97.0	97.5
Loss, percent	1.5	2.0	1.3

*Tetraethyl lead.

TABLE 3

Approximate range of quality of 7-lb. R.V.P.* aviation gasolines obtained by two-pass TCC processing with clay catalyst

Acid heat, °F.	10 to 25
Accelerated-gum test (5 hour), mg. per 100 ml.	3 to 5
Aromatic content, percent by volume	20 to 30
Octane No. (AFD-1C)†	
Without TEL addition	77 to 80
With addition 3 ml. TEL per gal.	92 to 95
With addition 4 ml. TEL per gal.	94 to 97
100-octane-number alkylate blend‡ plus 4 ml. TEL per gal., percent by volume of alkylate.	22 to 45

*Reid vapor pressure.
†AFD-1C=1C method, Aviation Fuels Division, CFR committee.
‡This gasoline has the necessary combustion characteristics to permit it to comply with latest aviation-gasoline specifications.

fact that the process is equally adaptable to the production of motor gasoline and high-octane aviation gasoline.

Due to the restrictions imposed by war conditions, it is not possible to publish herein detailed data regarding the performance of the TCC process. Considerable data have been developed concerning the production of motor and aviation gasolines, which data show that the TCC process gives yields and products comparing favorably with those from other catalytic cracking processes employing similar catalysts. Although these results cannot be published for general use, they are available to potential licensees through the licensing agents for the process. However, the following discussion will give a general idea as to the type of results obtained from the process.

Motor-Gasoline

Motor gasoline is produced by the cracking of distillate stocks, either once-through or with recycling. Within the range of variables outlined previously, once-through operations give motor-gasoline yields of 35 to 62 volume percent on gas-oil charging stocks. Similarly, operations employing recycling of catalytic gas oils give motor-gasoline yields of 50 to 85 percent. Motor-gasoline yields of 35 to 45 percent single-pass, and of 50 to 60 percent with recycling, are representative of commercial proposals. Recycling operations are preferable, from the standpoint of ultimate yield, as the first step in the production of aviation gasolines. Typical single-pass and recycle cracking operations on gas oil are exemplified by cases "A" and "B" in Table 1. Properties of typical motor gasolines obtained from various stocks are shown in Table 2.

Aviation-Gasoline

Aviation gasoline of excellent quality is produced by the reprocessing of the first-pass motor gasoline in a TCC reactor operated on a once-through basis, at somewhat lower throughput rates than in cracking. This second-pass operation, which yields 80 to 95 percent of the aviation cut present in the motor-gasoline charge, serves primarily to improve the leaded octane numbers, oxidation stability, gum stability, and aromatic content of the aviation fraction. A few general data on quality of two-pass TCC aviation gasolines are shown in Table 3.

Other Products

The two-pass operations described previously herein will yield, in addition to gasoline, a butylene fraction as high as 8 percent by volume of the gas oil. This can be increased considerably by cracking at elevated temperatures, without undue sacrifice in gasoline yield.

The yield of butanes, of which more than half represents *iso*butane, is generally of the order of 5 to 8 percent, and is not increased by severe cracking.

The potential yield of alkylate from the butylenes available in the total butane-butylene fraction from a two-pass

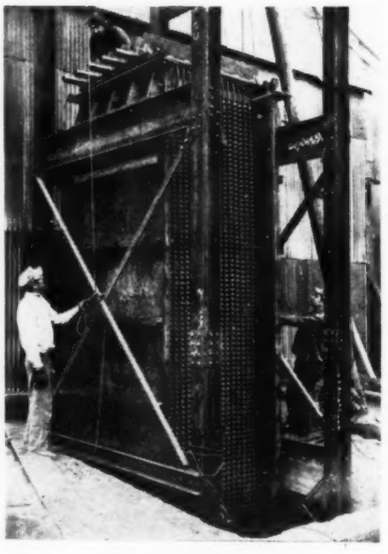

Fig. 6. View of spiral-fin type of Thermofor kiln

TCC operation for aviation gasoline will supply a substantial portion of the total alkylate requirement for the blending of aviation gasoline to 100-octane number. In addition, the two-pass operation yields an excess of *iso*-pentane concentrate over that required to pressure the total 100-octane-number blend of alkylate and base stock to 7 lb. Reid vapor pressure.

Other valuable by-products available in substantial quantity from TCC operations include: aromatic hydrocarbons such as benzene, toluene, and xylenes; naphtha fractions of high aromaticity and high octane rating; olefin-rich fuel gas, of which 35 to 40 percent by weight represents chiefly propylene plus some ethylene; and catalytic gas oil, of which from 60 to 100 percent will meet No. 2 fuel-oil specifications, depending on the endpoint of the gas-oil charging stock.

Summary

From the standpoint of the national emergency, the features of the TCC process may be summed up as follows:

1. Good yields of 100-octane-number aviation-gasoline blending stocks and butane-butylene cut for alkylation-plant charge.
2. Substantial yields of by-products, including heating oils, aromatics, and propylene.
3. Low construction cost and adaptability to existing refinery equipment, bringing catalytic cracking within reach of small refiners.
4. Low requirements for alloy steels and other strategic materials.
5. Flexibility with respect to type of operation and character of charging stock.
6. Conversion of excess heat obtained from catalyst regeneration into high-pressure steam.
7. Adaptability to wartime and peacetime production basis.

Future Outlook

In the post-war period the TCC process will find wide application for manufacturing catalytic motor gasoline of high quality. There appears to be little doubt that post-war gasoline manufacturing operations will find catalytic cracking displacing thermal cracking to an ever-increasing extent. Aviation-gasoline manufacture and the demand for greater quantities of butylenes probably will continue at a rate intermediate between the pre-war and wartime requirements. The TCC operation will meet these requirements in excellent fashion because of its broad range of flexibility. Likewise, with emphasis being placed on low operating and investment costs, the TCC process will maintain a strong position because of its outstanding characteristics in these respects.

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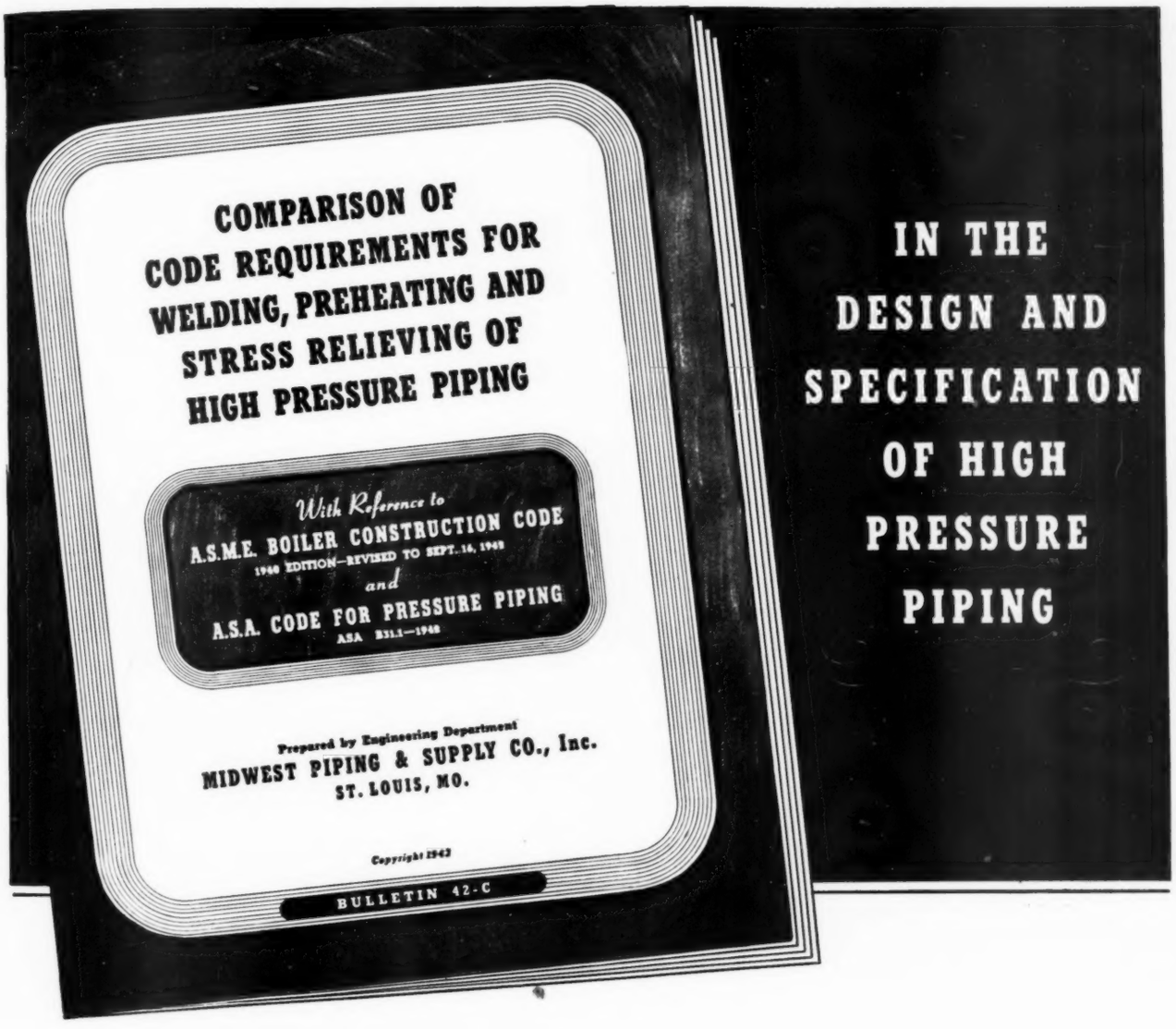

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War Developments in the Petroleum Industry*

By E. V. MURPHREE
Standard Oil Development Company

THE petroleum industry's contributions to the war effort have been numerous and varied. Undoubtedly, the most important of its contributions along manufacturing lines are production of synthetic toluene, of large quantities of high-octane aviation gasoline, and of raw materials for synthetic rubber. These processes give either pure chemical compounds or mixtures of definite types of chemical compounds and, therefore, represent organic chemical synthesis on an enormous scale.

Table I gives an overall picture of the new process developments and their relation to oil refining. A typical crude oil is broken down into various fractions which are then processed to obtain the products used in high-octane aviation gasoline or synthetic rubber raw materials.

Table I shows that the C_4 fraction can be converted into aviation gasoline through the alkylation process, using fractionation or isomerization or both. As an alternative, the butane fraction after separation of *iso*butane can be catalytically dehydrogenated by successive steps to give butadiene. The C_5, C_6, and C_7 fractions (boiling up to 200°F.) can be used directly in aviation gasoline, or selected fractions of these cuts can be isolated by fractionation and used in aviation gasoline. The low octane number fractions discarded in the fractionation can be isomerized into fractions of higher octane number. The fraction boiling from 200 to 290° F. contains most of the potential as well as the actual C_7 and C_8 aromatic compounds, such as toluene and the xylenes. This fraction is preferably processed by hydroforming to convert potential aromatics into actual aromatics. The hydroformed material can be used directly in aviation gasoline, or the aromatics can be isolated by extraction. The heavy naphtha boiling from 290° to 350°F. can be subjected to severe thermal cracking or reforming to yield butadiene and other desirable materials directly, or this fraction can be hydroformed. The gas oil fraction boiling from 350°F. to crude bottoms is best processed by catalytic cracking to yield aviation gasoline and raw materials for synthetic rubber. The lighter portion of this fraction can be subjected to severe thermal cracking to yield butadiene and other desirable products. The crude bottoms can be utilized in fuel oil.

Most of the processes discussed in Table I represent new tools developed in the last few years, and many of them are recent developments just now beginning to be applied. The vast amount of new equipment being installed for carrying out these processes represents an investment of nearly a billion dollars.

*Presented before American Chemical Society, Detroit, Michigan, April 12-16, 1943, and published in *Industrial and Engineering Chemistry*, June, 1943.

Superfractionation

Distillation is the oldest process for separating petroleum into its constituents. Application of fractional distillation to give extremely narrow-cut fractions is, however, a commercial development of rather recent application in petroleum refining and has been termed "superfractionation." By careful analysis of the lighter fraction of crude oil it has been found that certain constituents, particularly the *iso* or branched-chain compounds, have higher octane number or antiknock properties than others. Furthermore, *iso*butane is one of the raw materials for the alkylation process. Fractionation is applied for isolating *iso*butane from the C_4 fraction. *Iso*pentane has a considerably higher octane number than *n*-pentane and is therefore being isolated in many cases by fractionation from the C_5 fraction.

Alkylation

Alkylation is a process of relatively recent origin by which *iso*paraffins are combined with olefins to give higher molecular weight compounds of branched-chain structure. From a commercial standpoint the *iso*paraffin used is *iso*butane, which can be combined with propylene or C_4 or C_5 olefins. The reactions involved, the major products obtained, and the octane number of part of the product known as aviation alkylate which can be used in aviation gasoline are shown in Table 2. A catalyst is used in the alkylation reaction; for the C_3, C_4, and C_5 olefins, sulphuric acid or hydrofluoric acid may be employed. A flow sheet of alkylation of C_4 olefins with *iso*butane is shown in Fig. 1.

The fresh feed consisting of *iso*butane and C_4 olefins, which may contain some *n*-butane, is introduced into a reaction medium consisting of an emulsion of hydrocarbon and sulphuric acid. This emulsion circulates continuously through a reactor and then through a heat exchanger to remove the heat of reaction. Hydrocarbon fraction roughly equivalent in volume to the feed is drawn off to a fractionation system which separates the *iso*butane and returns it to the reaction system. The *n*-butane introduced with the feed is discarded, and the alkylate produced is separated from a small amount of polymer of higher molecular weight.

Alkylation is carried out on a large scale today for production of high-octane aviation gasoline blending agent. The *iso*butane required is fractionated from the butane fraction in crude oil production or in refining operations, or produced by isomerization of the *n*-butane obtained in this way. The olefins used as raw material for alkylation are obtained from cracking, primarily from operations involving catalytic cracking; for example, one catalytic cracking process, operated under normal conditions, will yield about 31 volume per-

Fig. 1. Alkylation process

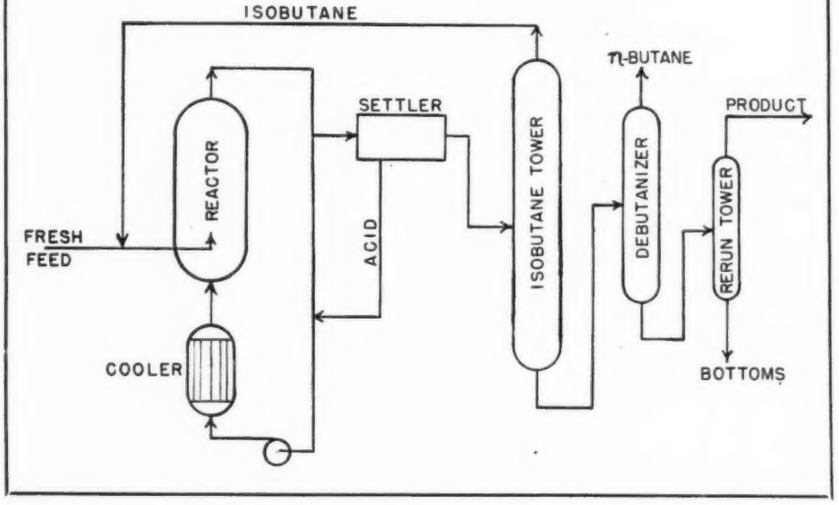


TABLE I
Processing of crude oil

Fraction	Percent on crude	Processes used	End use
Gas	0.7	Direct	Fuel
C_4	1.7	Fractionation, Isomerization, Alkylation	Aviation gasoline
		Dehydrogenation	Butadiene
C_5	2.6	Direct	Aviation gasoline
C_6	3.0	Fractionation	
C_7 (200° F.)	4.3	Isomerization	
200°–290° F.	11.2	Direct	Aviation gasoline
290°–350° F.	7.0	Hydroforming	Synthetic aromatics
		Severe thermal cracking	Butadiene
350° F., crude bottoms	57.5	Catalytic cracking, Severe thermal cracking	Aviation gasoline, Butadiene, Isobutylene for Butyl rubber

cent of C_2 through C_5 olefins, based on the gas oil charged.

Isomerization

Isomerization involves rearrangement of a compound without change in molecular weight. Its most important commercial application in the petroleum field is the conversion of *n*-butane to *iso*butane. This reaction is carried out normally with aluminum chloride as catalyst. Owing to equilibrium limitations, only part of the *n*-butane is converted to *iso*butane per pass. The *iso*butane obtained can either be isolated by fractionation or directly fed to an alkylation process. By combining isomerization of *n*-butane with alkylation, some saving is achieved by the use of common fractionation equipment. Fig. 2 indicates the flow in such an isomerization plant.

C_5 and higher straight-chain hydrocarbons can be isomerized to branched-chain hydrocarbons; this treatment improves their antiknock properties. *Iso*pentane, *iso*hexane, and *iso*heptane are valuable compounds for use in high-octane aviation gasoline. In the case of the C_5 and higher hydrocarbons, there is a tendency for cracking to occur during isomerization, and the olefins produced form complexes with the aluminum chloride. These complexes are very active, particularly for cracking, but have little selectivity for isomerization. For this reason it is desirable to carry out the isomerization of the C_5 and higher hydrocarbons under conditions where the olefin complexes are suppressed.

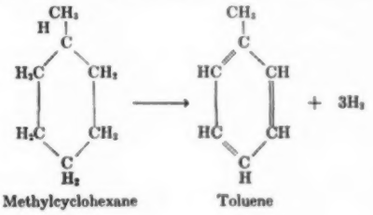
Hydroforming

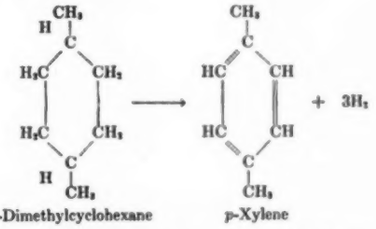
Catalytic dehydrogenation is effective for converting C_6 and higher normal paraffins and six-carbon ring naphthenes into aromatics. When applied to fractions of naphtha from crude, catalytic dehydrogenation yields large quantities not only of aromatics but also of coke, and the cost of equipment involved in burning off coke from the catalyst is high. To decrease coke formation, dehydrogenation is carried out under hydrogen partial pressure. This operation, involving catalytic dehydrogenation in the presence of hydrogen, in known as hydroforming.

In its present commercial application, naphtha vapor along with recycled hydrogen is passed through a fixed catalyst bed for a certain time. During this dehydrogenation operation, there is a net production of hydrogen. Coke deposition on the catalyst is not completely eliminated, so that the catalyst must be periodically regenerated by burning with air or oxygen-containing flue gas. Normally two or more reactors are provided; one reactor is used for dehydrogenation while a second is being regenerated.

Fig. 3 is a typical flow sheet. Naphtha vaporized in a furnace is mixed with hot recycled gas which contains a high percentage of hydrogen. This mixture flows through the reactor and then to condensing equipment where the product is removed. The cooled gas is recycled back to the feed end of the system. Excess gas is removed by purging and can be used for certain types of hydrogenation. Some cracking occurs in the dehydrogenation operation, and the products are separated by fractionation. If it is desired to isolate pure aromatics, the proper fraction of hydroformed material is subjected to extraction.

Hydroforming produces aromatics primarily by dehydrogenation of C_6 naphthenes and is not effective for obtaining aromatics from paraffins. As an example, toluene is produced by dehydrogenation of methylcyclohexane; xylenes are obtained by catalytic dehydrogenation of dimethylcyclohexane:

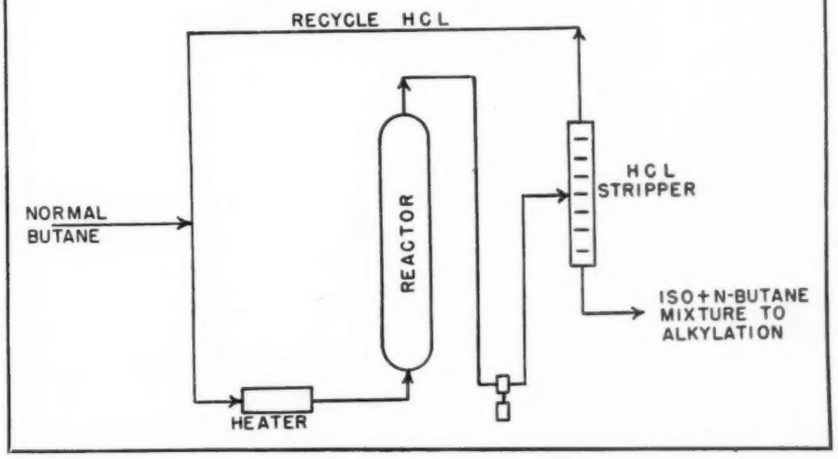




In addition, certain amounts of toluene and xylenes may be produced by cracking higher alkylated aromatics, either present in the feed or produced during hydroforming. There is also some formation of aromatics from alkylated C_5 naphthenes which presumably are first isomerized into C_6 naphthenes.

The first major wartime application of hydroforming has been to produce synthetic toluene for TNT. The first commercial plant, which has been in operation for a considerable time, is making toluene at a rate equivalent to about twice that produced by the whole coal

Fig. 2. Isomerization of n-butane



tar industry. Without the hydroforming process, this country would be in a serious position in regard to toluene supplies. Additional plants for synthetic toluene have been installed. When the proper naphtha fraction is used, the hydroforming processes will produce high quality aviation gasoline and will probably be widely utilized for this purpose.

Catalytic Cracking

Cracking has been described as a process for making little ones from big ones—that is, for converting higher into lower molecular weight hydrocarbons. Cracking can be accomplished by heat alone (thermal cracking) or by the action of a catalyst under conditions which give negligible thermal cracking (catalytic cracking). The catalyst not only accelerates but also directs the course of the cracking reaction to give better yields of higher quality products. During the course of a cracking reaction, the catalyst becomes fouled and must be revivified by removal of the tar or coke by burning with air.

Three types of catalytic cracking are being widely applied—the Houdry, the Fluid Catalyst, and the Thermofor processes. The Houdry process utilizes the conventional fixed-bed principle. Oil vapor is passed through a fixed catalyst bed where cracking occurs. The cracked products are separated into desired constituents by fractionation. After cracking has been carried out for a certain time in one reactor, the oil vapor stream is switched to another reactor while the first reactor is regenerated by burning the coke off the catalyst with air. Generally several reactors are used. By switching the oil vapor stream from one reactor to another, cracking is continuous. The reactors are treated intermittently through alternate cycles of cracking and regeneration.

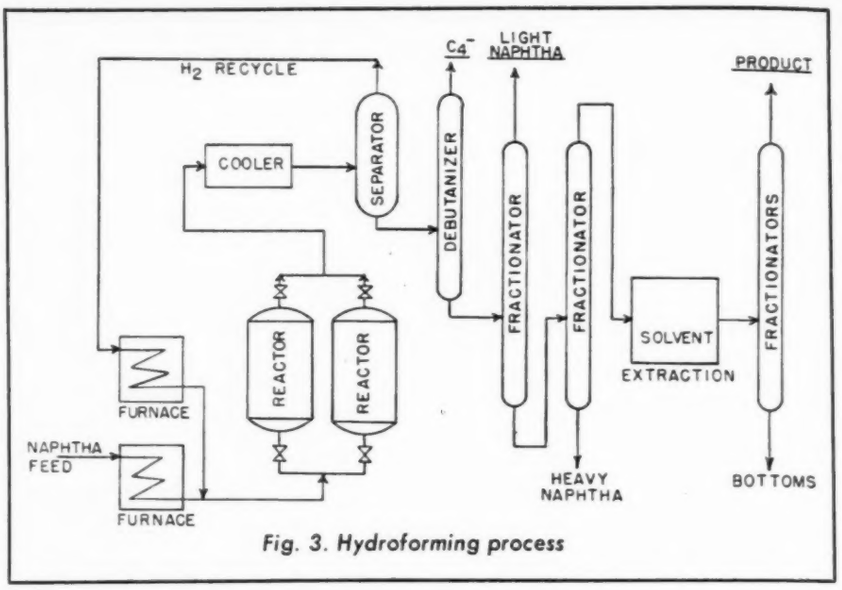


Fig. 3. Hydroforming process

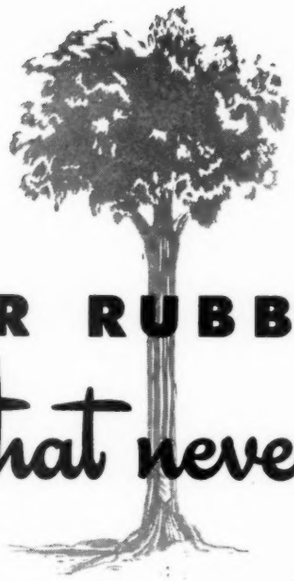
In the Fluid Catalyst and Thermofor processes, catalyst is continuously circulated through a reaction vessel, then to a regeneration vessel, and back to the reaction vessel. These processes are truly continuous. The Thermofor process uses catalyst in the form of coarse granules and mechanical conveyors for circulation. In the Fluid Catalyst process, circulation is accomplished by principles not previously applied commercially. In both processes, oil normally in the form of vapor is passed through the reactor where cracking occurs, and cracked products are sent to suitable fractionation equipment. Air is blown through the regenerator for burning the coke deposited on the catalyst. Both the Houdry and Thermofor processes have already been discussed[1, 2] rather fully.

The Fluid Catalyst operation represents a new industrial method of handling solids and of controlling the temperatures of gaseous or vapor reactions. The catalyst is used in the form of powder, maintained in a free-flowing or fluid condition at all times. Circulation of catalyst in large quantities between the reaction or cracking vessel and the regeneration vessel is accomplished without moving parts, by application of the gas lift principle for handling liquids. Pressure to promote catalyst circulation is built up by a standpipe containing catalyst of high density which provides a gravity fluid head against a catalyst leg of lower density. The amount of pressure that can be built up depends only on the height of the standpipe.

Fig. 4 shows the principle of the Fluid Catalyst process. Catalyst from a standpipe is introduced into the oil vapor entering the system and is carried by the oil vapor up into a reaction vessel of relatively large cross section. The mixture of catalyst and cracked products flows from the top of the reaction vessel into a cyclone separator where the bulk of the catalyst is separated from the products. The cracked products pass on to fractionation equipment. The spent catalyst, which contains some coke deposited from the cracking reaction, flows from the cyclone separator to a hopper and then down a standpipe where a high

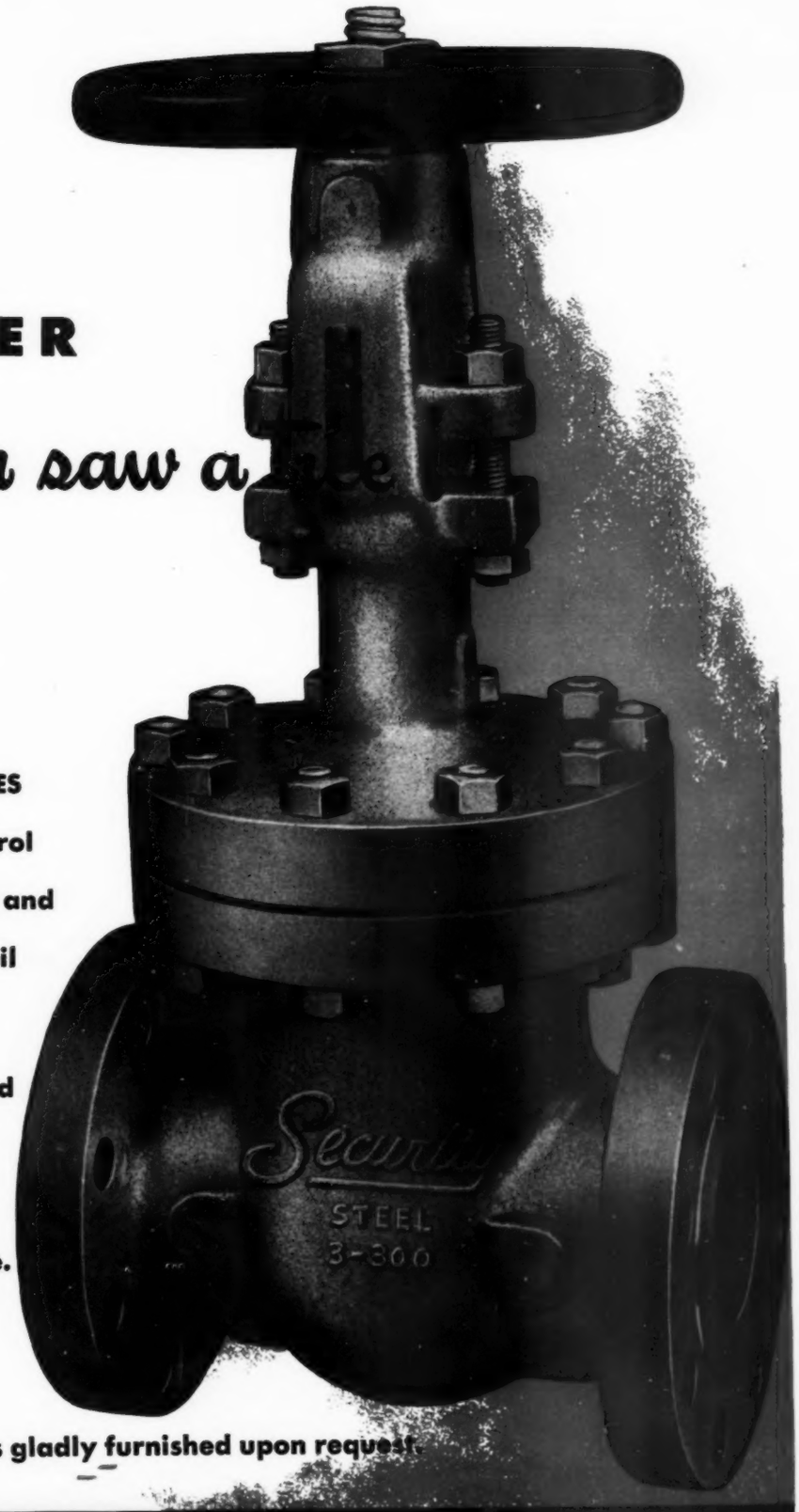
TABLE I
Alkylation reactions

Raw Material	Main Products	A. S. T. M. Octane No. of Aviation Alkylate
Isobutane + Propylene	2,3-Dimethylpentane	87–89
	2,4-Dimethylpentane	
Isobutane + 2-Butene	2,2,4-Trimethylpentane	93–95
Isobutane + Isobutylene	2,3,3-Trimethylpentane	
	2,3,4-Trimethylpentane	



FOR RUBBER

that never saw a tree



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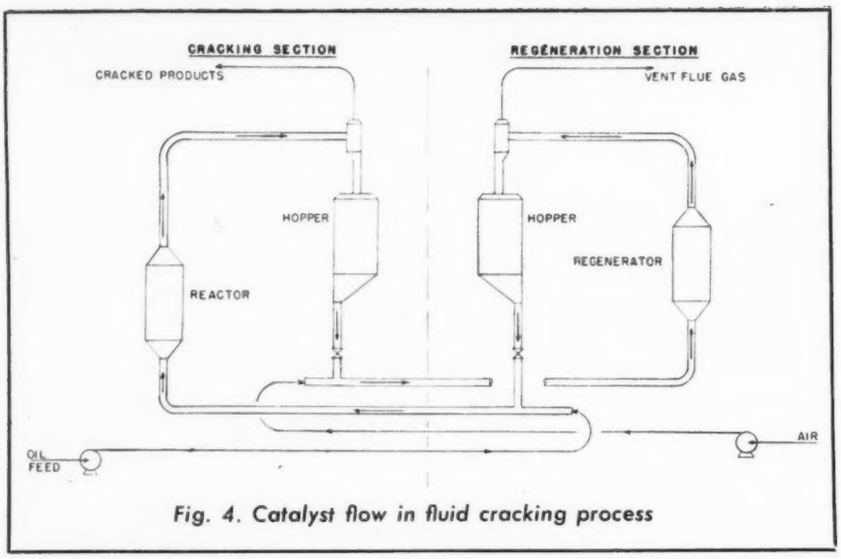


Fig. 4. Catalyst flow in fluid cracking process

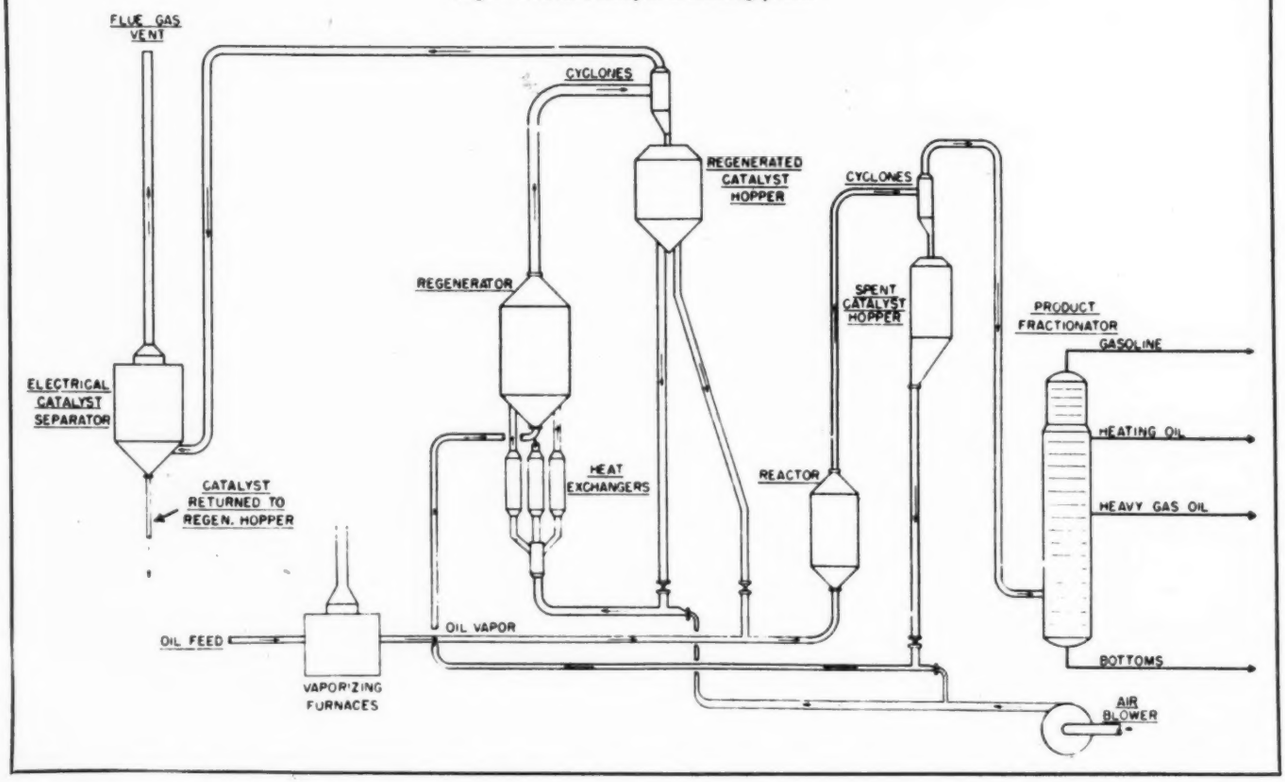
density is maintained to build up pressure. From the standpipe the spent catalyst flows by gravity into an air stream and is blown up into the regeneration vessel, which is also relatively large in cross section. The mixture of flue gas and regenerated catalyst flows from the top of the regeneration vessel into a cyclone separator where the bulk of the catalyst is separated from the flue gas. The regenerated catalyst flows into a hopper and then down a standpipe where high catalyst density is maintained to build up pressure. From the standpipe the regenerated catalyst again flows by gravity into the oil vapor stream to complete the cycle.

The upward velocity of oil vapor or air in the regeneration and reaction vessels is low. There is a tendency for the catalyst to settle out against the upflowing gas or vapor stream; as a consequence it is possible to build up a relatively high catalyst density in these vessels. The catalyst is nevertheless extremely turbulent; in many aspects it resembles a boiling liquid, and therefore, very uniform temperatures can be maintained throughout the catalyst mass in these vessels.

Fig. 5 gives a flow sheet of one type of design for a Fluid Catalyst cracking plant, which is similar in principle to Fig. 4. Oil is vaporized in a furnace and enters the catalytic section of the plant. Regenerated catalyst flowing down a standpipe is introduced into the oil vapor stream and is blown up into the reaction vessel, in which a relatively high catalyst density is maintained owing to the settling action of the catalyst against the vapor flow. Catalyst and cracked products pass to a series of three cyclone separators where essentially all of the catalyst is removed. Cracked products containing a small amount of catalyst flow to the product fractionating system. The catalyst separated in the cyclone separators is collected in a spent catalyst hopper and from there flows down a standpipe to meet the regeneration air stream, which carries it into the regenerator. Owing to the slipping action of the catalyst, a high relative density of catalyst is maintained in the regenerator. The mixture of flue gas and catalyst from the regeneration vessel passes first to a series of three cyclone separators and then to an electrical precipitator for catalyst recovery.

The flue gas leaving this dust collecting system contains only a minute amount of catalyst. The catalyst from the dust separation equipment is collected in a hopper, from which the regenerated catalyst flows down two

Fig. 5. Fluid catalyst cracking plant



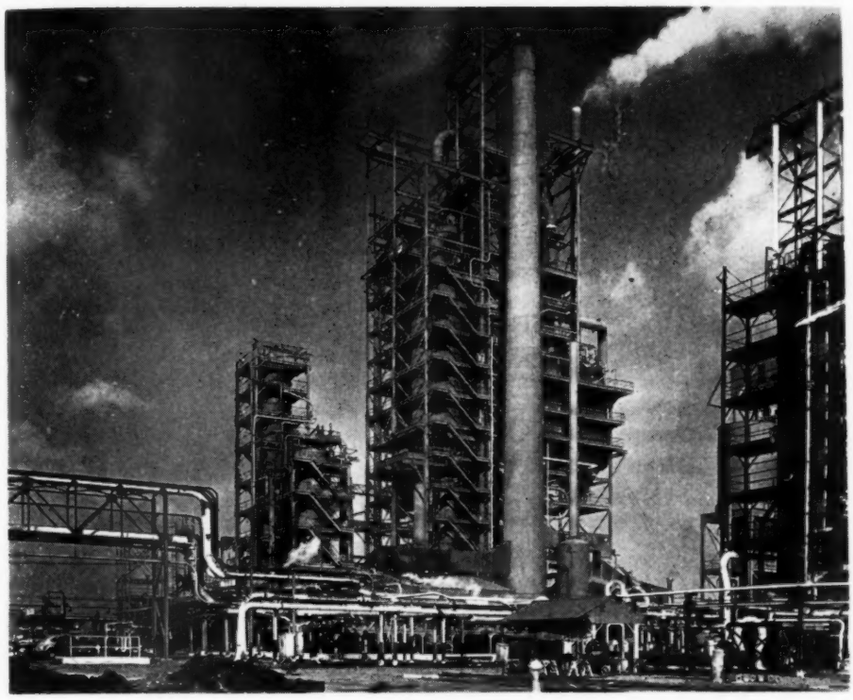


Fig. 6. Commercial fluid catalyst unit

standpipes. The catalyst flowing down one of these standpipes meets fresh oil vapor and thus completes its cycle. The catalyst flowing down the other standpipe meets a small quantity of regeneration air and is blown up through tube-and-shell coolers which assist in removing the heat evolved in burning off the catalyst. This quantity of heat in the design of the plant shown is normally much greater than can be put into the oil through the hot regenerated catalyst. The heat removed in the tube-and-shell coolers may be used for preheating oil, generating steam, and other purposes.

The cracked products which leave the catalytic system pass to suitable fractionating equipment. Normally this fractionating equipment will isolate the C_4, C_5, aviation gasoline boiling above C_5, heavy naphtha, domestic heating oil, and heavy cycle gas oil fractions. The *iso*butane and C_4 olefins go into alkylate for aviation gasoline, or some of the C_4 olefins may be used in the production of raw materials for synthetic rubber. The C_5 fraction may either go directly into aviation gasoline or be subjected to further processing before such use. The catalyst carried over by the cracked products is collected at the bottom of the primary fractionation tower, and may be pumped back to the catalyst system as a slurry in cycle gas oil or be returned to the catalytic system by other means.

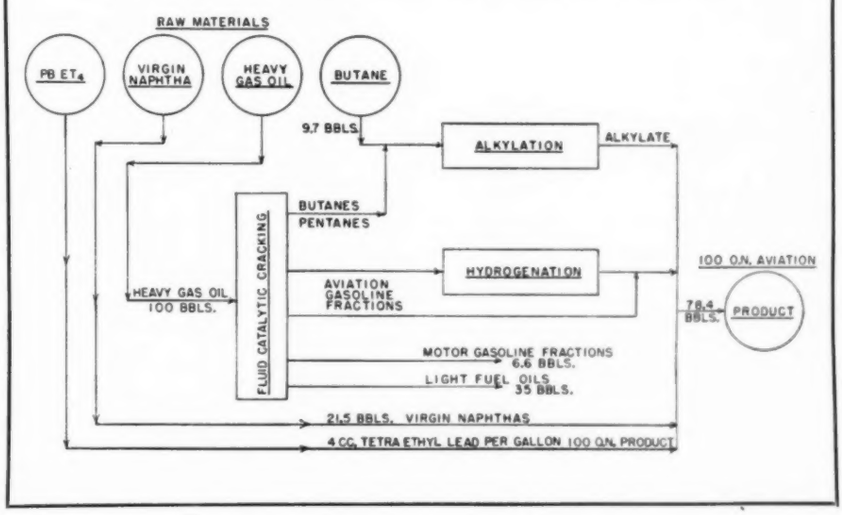
Three large Fluid Catalyst cracking units are now in successful commercial operation, and a large number are being erected. Fig. 6 is a photograph of one unit.

The Fluid Catalyst principle has an important application to controlling the temperatures of vapor or gaseous reactions, whether a catalyst is required or not. Where no catalyst is desired, an inert powder may be used to replace it. In vessels such as the reactor or regenerator in a cracking unit, the relatively high-density catalyst is in an extremely turbulent state. Because of this turbulence, the temperatures throughout the vessel are essentially identical. For example, in the regenerator of a typical large commercial unit, the heat liberated will be 120,000,000 B. t. u. per hour. With this high degree of heat liberation, the maximum difference found at different points of the vessel has been less than 5°F.; this probably reflects inaccuracies of measurement rather than any real difference in temperature. The catalyst or inert powder gives the mixture in the vessel heat capacity and thus guards against rapid temperature fluctuations. Heat can be removed or added to the system by circulation of catalyst through heat exchangers, as used on the regenerator in Fig. 5. The Fluid Catalyst principle can be applied here whether or not the catalyst needs revivification and even if no catalytic effect is desired. One application would be for controlling the reaction temperature in the oxidation of aromatic compounds, particularly for the production of phthalic anhydride from naphthalene. It is believed that the Fluid Catalyst principle may be applicable in metallurgical processes for reducing ores and other operations, and to all types of reactions involving temperature control of gases, vapors, or solids.

Aviation Gasoline

An indication of the source of high-octane aviation gasoline is given in Table I, which indicates means for processing virgin naphtha and gas oil for aviation gasoline. In general, virgin naphthas from certain types of crudes are of sufficiently high octane number to be used directly in aviation gasoline. Virgin naphtha of lower octane number can be isomerized or further processed to give naphthas of sufficiently high octane number to go into aviation

Fig. 7. Aviation gasoline production by fluid catalytic cracking



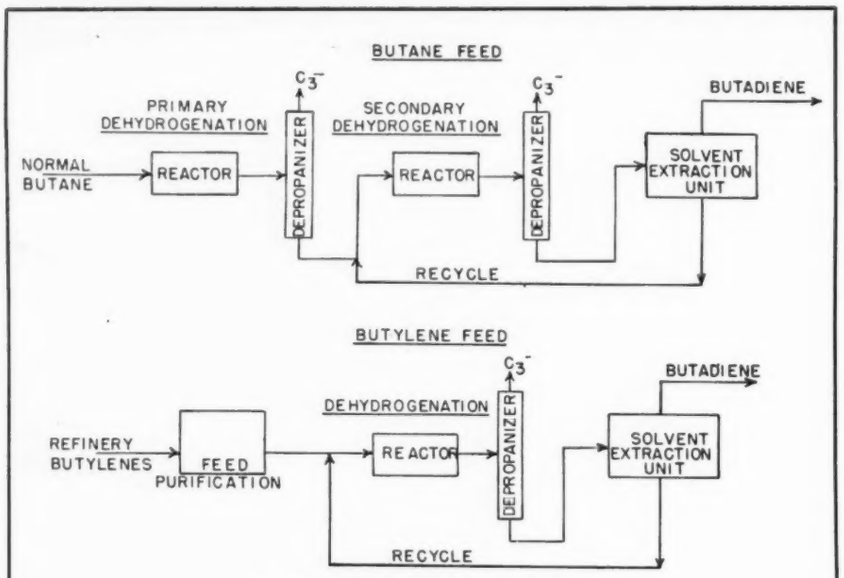


Fig. 8. Manufacture of butadiene

gasoline. Hydroforming may be applied to a virgin naphtha fraction having a boiling range of, say, 200° to 300°F. for preparation of an aromatic blending agent to be used in aviation gasoline. To convert gas oil into aviation gasoline and aviation gasoline raw materials, such as *iso*butane and butylenes, catalytic cracking has most general applications. Fig. 7 illustrates the application of one type of catalytic cracking to aviation gasoline production. From 100 bbl. of gas oil charged plus 9.7 bbl. of *iso*butane, 56.9 bbl. of aviation gasoline are produced. This gasoline is considerably higher in octane number than existing specifications require; it is possible to blend in 21.5 bbl. of virgin naphtha, which is not sufficiently high in octane number for direct use, to give a total of 78.4 bbl. of aviation gasoline meeting 100-octane specifications for each 100 bbl. of gas oil cracked. This operation involves alkylation of olefins and some further processing of a portion or all of the catalytic naphtha. In addition to the 78.4 bbl. of aviation gasoline 6.6 bbl. of heavy naphtha are produced for motor gasoline and 35 bbl. of cycle gas oil. The latter may be further processed or used as light fuel oil. Catalytic cracking is essential for the large quantities of high-octane gasoline required for the war.

In addition to catalytic cracking, hydrogenation is being applied on a limited scale for production of aviation gasoline from gas oils. In general, where new equipment is involved, hydrogenation is not so attractive as catalytic cracking. Hydrogenation is also being applied for converting certain olefinic polymers to high-octane saturated compounds suitable for use in aviation gasoline.

Butadiene

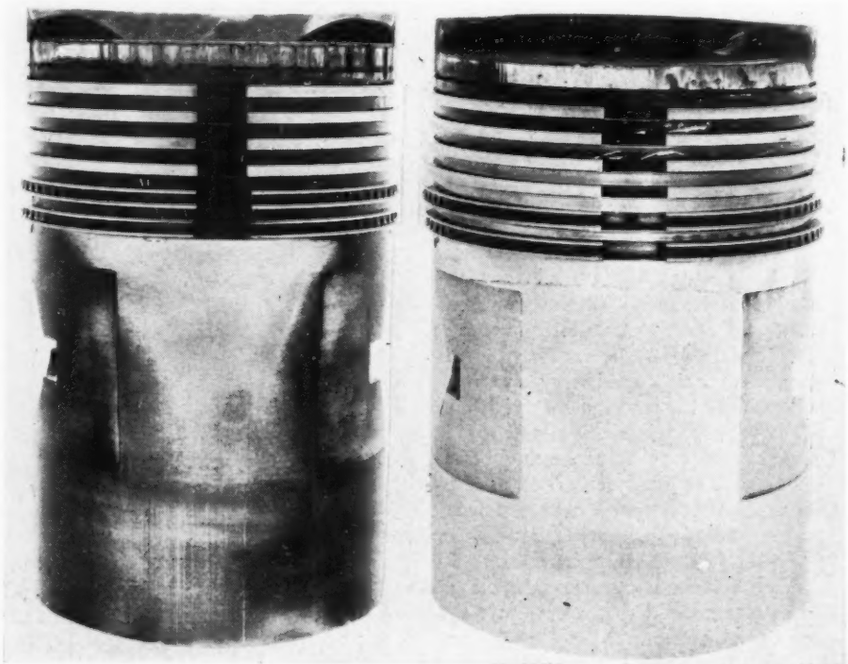
Butadiene for synthetic rubber is being produced both from *n*-butane obtained from natural gas fields or refinery operations and from *n*-butylenes obtained from cracking, particularly catalytic cracking. In addition, a certain amount of butadiene is being obtained from severe thermal cracking. The latter is part of the so-called quick butadiene program.

Butadiene from butane is really a two-step operation involving, first, the production of *n*-butylene from *n*-butane and then the conversion of *n*-butylene to butadiene. Both steps are carried out in the presence of a catalyst. Production of butadiene from refinery butylenes involves, first, the segregation of *n*-butylenes and then the conversion of *n*-butylenes to butadiene through the use of a catalyst. The processes being applied for converting *n*-butane to butadiene were developed by Universal Oil Products Company, Phillips Petroleum Company, and Houdry Corporation. The process for conversion of refinery *n*-butylene to butadiene was developed by Standard Oil Development Company. Schematic flow sheets of the processes starting with *n*-butane and with refinery butylenes are shown in Fig. 8.

Starting with field butane, the *n*-butane must first be isolated. It is then converted in two catalytic stages into butadiene; the conversion per pass, however, is incomplete. Lighter products are separated between both steps; they are hydrogen and cracked products. The C_4 fraction isolated after the second catalytic step is subjected to extraction to remove butadiene. Unconverted C_4 fraction is recycled. Where refinery butylenes are the starting material, *n*-butylenes must first be segregated, although in this step it is

Fig. 9. Pistons from laboratory single-cylinder Diesel test engine

After 500 hours on high-quality mineral oil *After 1000 hours on oil containing detergent*



not essential to produce a fraction of high purity. This *n*-butylene fraction is then subjected to catalytic dehydrogenation; some cracking occurs and the conversion is not complete. The product is fractionated to give a C_4 fraction containing the butadiene. This fraction is then extracted to remove the butadiene, and the unconverted material is recycled. Equipment is being installed to produce butadiene from both raw materials on a relatively large scale. The major portion of butadiene from oil will, however, be made from refinery butylenes.

The synthetic rubber program involves production of Butyl rubber on a relatively large scale. The main raw material for Butyl rubber is *iso*butylene which can be extracted from refinery C_4 fraction. The bulk of *iso*butylene for Butyl rubber will originate from catalytic cracking.

Other Developments

Much of our military equipment requires lubricating oils with detergent properties contributed by special addition agents. Oils containing these agents tend to keep carbon and lacquer deposits from forming on various parts of the engine. Fig. 9 shows engine parts after tests on the same base oil under the same conditions, with and without an addition agent. The difference in cleanliness is striking.

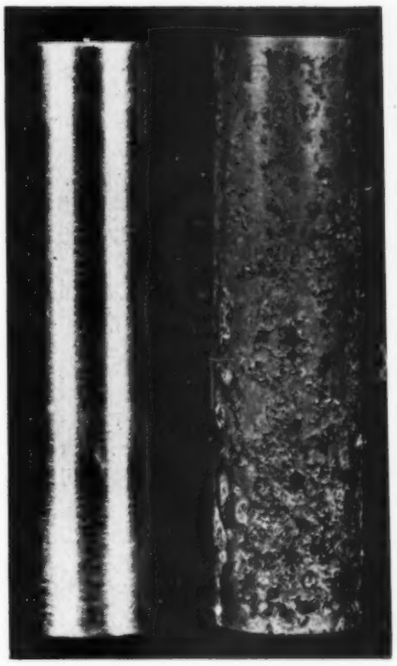
Movement of parts of airplanes, cannon, and other military equipment is controlled by transmission of pressure by a fluid generally called a "hydraulic oil." As the equipment is subjected to widely varying temperatures, especially to very low temperatures, hydraulic oils must have a slow change of viscosity with temperature. Straight petroleum oils have too great a viscosity variation with temperature, but certain substances can be added to give the desired property.

Addition agents are also used to produce an asphalt suitable for construction of roads and runways of airports under wet conditions. Normally asphalt, when mixed with wet aggregate, will not give a bond that adheres; hence roads or runways built in wet weather will probably distintegrate. Addition of small amounts of certain materials alters the asphalt so that it will adhere to wet aggregate. Fig. 10 shows results of coating tests on wet aggregate, with and without an addition agent, after immersion in water for 20 hours.

Military equipment must be shipped by water for long distances. Without suitable protection it will corrode and reach its destination in an unusable condition. The industry has met the need for rust-preventive coatings with petroleum oils containing special agents to give adhering films and to prevent rust. Many of these oils have the property of displacing water from metal surfaces. Results on exposure of two metal rods, one coated with a rust-preventive oil and the other with straight mineral oil, to hot moist air in a laboratory test are shown in Fig. 11.

Developments in military equipment have made necessary new types of greases and of process and industrial oils. The petroleum industry has been successful in meeting these requirements.

Production of synthetic ethyl, *iso*propyl, and higher alcohols, as well as their derivatives, is continuing on an increasing scale. Naphthenic acids, phenols, and vanadium are being obtained from petroleum. Many new organic developments are based on petroleum. The future holds great promise in this field.



Rust-preventive oil *Straight mineral oil*

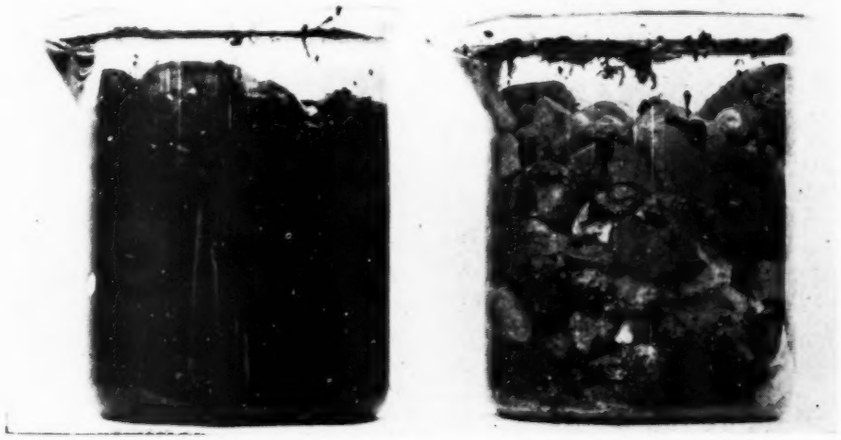
Fig. 11. Effect of coating on protection against corrosion

Strides have been made in the use of petroleum as an offensive weapon along two lines—the production of new or improved equipment for applying petroleum, and the conversion of petroleum into forms more suitable for use. Through research carried out by the petroleum industry in cooperation with the Chemical Warfare Service and the Office of Scientific Research and Development, destructive incendiary bombs have been developed. Improvements have been made in chemical and smoke bombs. The effectiveness of flame throwers has been greatly increased. Smoke generators of outstanding efficiency have been produced.

Many of the processes discussed are the result of cöoperative developments. The petroleum industry is working together as a team. In meeting war problems the industry has freely exchanged information on new processes and new products through the facilities provided by the Petroleum Administration for War. In this way the experience of any one unit in the industry has been shared by all.

Fig. 10. Water-soaked gravel coated with asphalt after 20-hour immersion test

Treated *Untreated*



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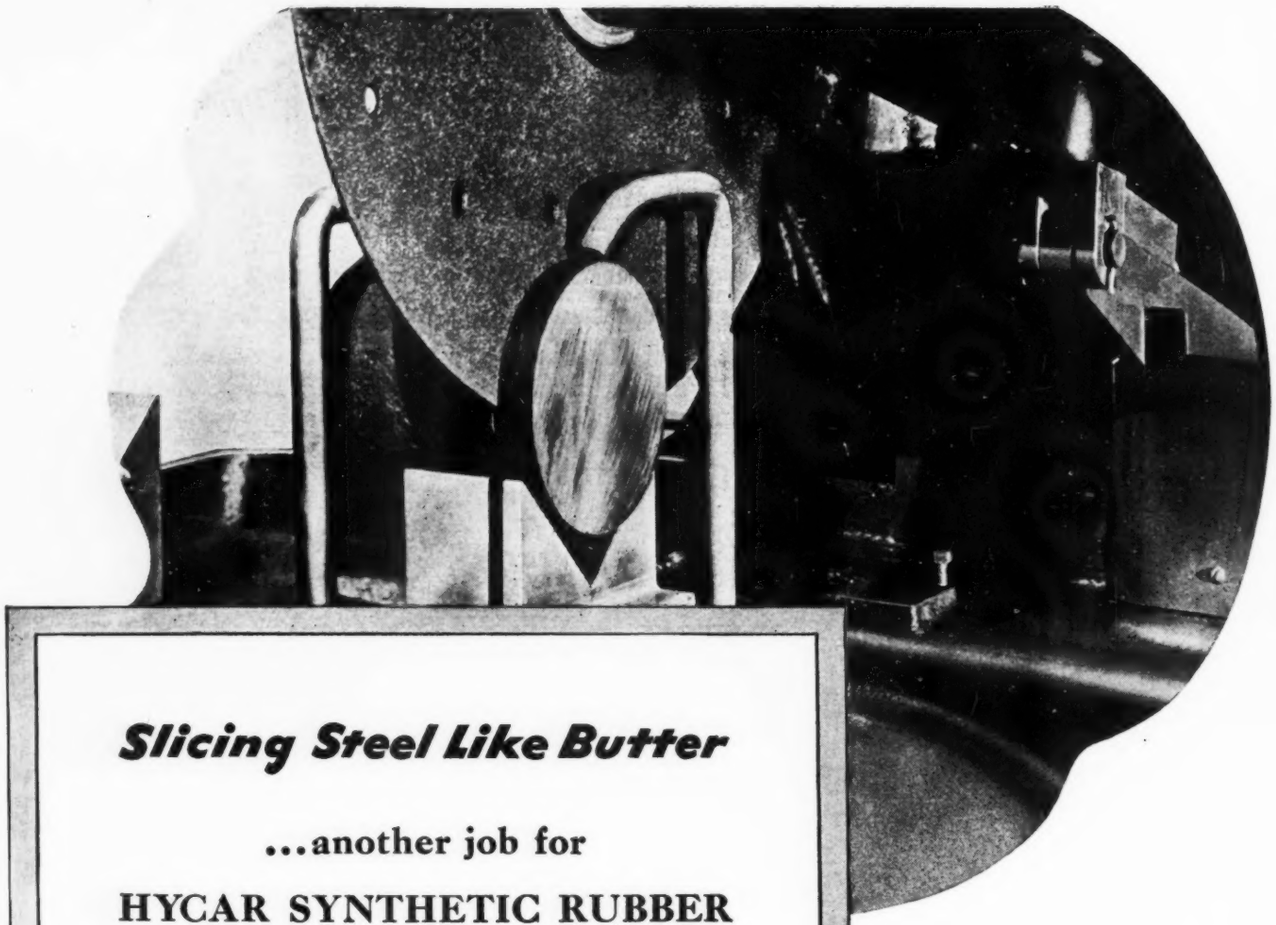

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Metallizing in the Refinery*

By
J. E. YOUNG, SR.
General Metallizing and Machine Company

THE refiner is confronted with a multitude of new problems every day. Not the least of these is that of keeping the plant equipment in repair. Many of the larger refineries have used the metallizing process for one or more applications for several years past. In recent months they have found it a necessity rather than a convenience in a host of everyday applications. By its use, worn parts can be repaired and put back in service in about the time it would take to get a requisition to the purchasing department for a new part.

The metallizing or metal spray process is not something new. Its use in other lands began many years ago. In this country the real development has been in the last 18 years. The equipment has been continually improved so that the work can be done much faster and the results are better than that of even a few years ago. One of the greatest improvements has been in adapting the equipment to the use of liquefied petroleum gases as fuel.

The metal deposited by this process is somewhat porous. This characteristic is very valuable when the metal is used for erosion or wear resistance. The pores on the finished surface hold tiny drops of lubricant much better than a forged or rolled surface. When used as a corrosion resistant the porous quality generally makes it necessary to build up a thicker coat to prevent liquids and gases from penetrating to the base metal. Sprayed metal used for wear resistance will generally last longer than the same metal in any other form.

The hardness of sprayed metals is about the same as for metals of the same specifications in rolled, cast or forged sections. Ordinary methods of hardness testing do not give accurate results when applied to sprayed metals because of the porosity. The lower density of this metal is due to oxides being included as the metal is deposited. With a neutral flame there will be no oxidization in the melting zone. However, the metal is broken up and carried by a stream of compressed air. Enough oxygen is picked up from the air to cause some oxidization. After the metal is deposited, it will oxidize slowly until it cools below the critical temperature. Some experimental work has been done along the line of substituting an inert gas for the air blast. The cost of this substitution is, as yet, too high to justify its use except in rare instances. When nitrogen is used for this purpose it has been found that some nitriding takes place. This may prove to be the next interesting development.

*Presented before Western Petroleum Refiners Association, Regional Technical Meeting, Shreveport, Louisiana, October 30, 1942.

Surface Preparation

It is understood, we believe, that this process does not weld the sprayed metal to the base metal. The bond between the two metals is purely mechanical. Hence, the preparation of the surface is all important. In preparing shafting and other elements that can be turned in a lathe, rough threading is the best method. After truing up the shaft, take a cut across the section to be sprayed, deep enough to allow for normal wear and still leave some of the deposit over the base metal. This allowance for most work can be about 3/32 in. on the diameter. If the shaft is very small in diameter, reduce this allowance accordingly. After completing the cut, square the ends and run a very rough thread on the entire section. For cast iron use about 16 threads per inch. As the base metal gets harder use a larger number of threads per inch. About 24 threads will be the maximum necessary. It cannot be emphasized too often that the thread cannot be too rough. The bottom of the thread groove should be slightly rounded and the sides well torn so there will be many cracks and crevices for the spray to lock around. To get this sort of thread there are several ways of grinding the tool bit. One simple way is to use a standard 60-deg. tool, rounding the point slightly and grinding off the top edges so there will be no clearance. Set the tool so the point is about 1/16 in. below the center and use a slow spindle speed. A few minutes' practice on some scrap metal will pay big dividends. For alloy shafts it is necessary to use very slow spindle speeds to get a well torn thread. In preparation of bronze, monel, and high nickel alloy steel shafts, it has been found advantageous to thread as above, then sandblast lightly. Do not hold the sandblast nozzle too close or some of the thread will be cut away. After a section is prepared, be careful to see that the surface does not become contaminated in any way. Onlookers have an irresistible urge to feel the surface. There is enough moisture on the hands to cause some trouble. Perspiration, grease, oil, dirt, and moisture will destroy the surface we have so carefully prepared. The best way to prevent contamination is to spray the section as soon as it is prepared.

All surfaces that cannot be prepared in the lathe must be sandblasted. The selection of the proper size and grade of grit, sand, or shot is important. Fine grains clean rapidly but leave a polished surface. The larger grains will clean and at the same time leave a rough surface. Steel grit is the most satisfactory blasting material. There are some localities where it cannot be used due to high humidity. The moisture will condense on the grit particles and in a few hours rust will form. When these particles are blasted against steel the tiny rust spots will be transferred to the steel being cleaned. This is very hard to detect but will surely cause trouble at a later date. In such localities a crushed flint brasive will give nearly as good results. After the grit selection is made, look to the air supply. Good blasting can be done only when the compressed air supply is adequate, clean, and dry. The pressure should be about 100 lb. at the blast machine. The diameter of the nozzle should be selected in relation to the size of the grit and the available supply of air. A nozzle ¼ in. in diameter will require about 105 c.f.m. of free air, while one 5/16 in. in diameter will take about 160 c.f.m. It is evident from these figures that the nozzle size should be selected to suit the air supply. Nozzles should be changed as soon as they show signs of wear. To remove mill scale and rust the nozzle is held about 6 in. from the surface. After the surface is clean, go over it all again rapidly, holding the nozzle about 15 in. away from the metal. This will produce the rough surface desired for the metallized coat. Do not blast a larger area than can be covered within a few hours. When the humidity is high, reduce the area blasted at a time so that there will be no oxide formed between blasting and spraying.

Spraying

After the surface is prepared correctly, the actual spraying operation should begin at once. For material prepared in the lathe, it is best to spray it in place or in a special turning device that will rotate the work at a uniform speed. Mount the metallizing gun in the tool post of the lathe and arrange the gas bottles in a safe, convenient place. The regulators should be within easy reach so any minor gas adjustments can be made as the spraying progresses. Blow out all hose so that no dirt will get into the gun; connect the hose to the regulators and the gun. With the gas bottle valves open, slowly screw in the regulators until the pressures reach

the proper figures for the metal that is to be sprayed. With the gun valve open wide, make any minor regulator corrections necessary. Close the gun valve and insert the wire in the gun. Light the gun, screw down on the wire feed, screw open the air cap to get the proper atomization, then point the gun at the section to be sprayed. The work should be revolving at about 60 r.p.m. The gun nozzle should be about 5 in. from the surface being coated. With the gun opposite one end of the section, spray until it is built up sufficiently to allow for machining operations. Move the gun along about ½ to ¾ of an inch and repeat until the entire section is sprayed. Unless the thickness of the sprayed metal must be over ¼ in., the preferred practice is to make the entire build-up in one pass of the gun. When thicker sections must be made, either use two passes or place an air blast on the rear of the shaft opposite the gun to provide the necessary cooling. In spraying it is best to keep the wire feeding through the flame at the maximum rate; that is, see that the flame is melting as much wire as possible. This will prevent the metal getting too hot and expedite the work. If the lathe is fitted with the proper cross feed gears, they may be used to move the gun along the section being sprayed. A little experience will soon show what speed is necessary to get the full thickness in one pass.

When spraying flat surfaces prepared by blasting, the gun is changed from the tool post mounting to the hand grip. The lighting is done in the same manner as described above. Estimate the sq. ft. in the area to be sprayed, weigh out the proper amount of wire for this area, and try to deposit it as evenly as possible. The deposit is made in several passes. The first pass is made moving the gun in a horizontal plane over a small area. The next pass is made moving the gun vertically over the same area. This alternation is continued until the correct thickness is obtained, when the next section is started. Always keep the gun pointing at the surface at right angles; otherwise, the spraying efficiency will be lowered due to some of the particles failing to stick.

In spraying the inside of refinery vessels that contain angles or other structural members, examine carefully to see that there is no open space between them and the shell. If there is such a space, it should be welded so the sprayed coat can be continuous, preventing gases and liquids from getting to the uncoated metal.

Lead, tin, cadmium, and babbitt should be wire-brushed thoroughly between each pass to remove most of the oxide that forms when spraying these metals. Denser deposits will result. If any grinding is done on sprayed metal on the inside of vessels, great care should be taken to see that the coat is not ground away in some spots.

For many years acetylene was the only gas available for metallizing fuel. About six years ago improvements were made in the equipment so that any petroleum gas under pressure can now be used. Hydrogen gas is being used in a few plants where it is available. At this time, propane is the cheapest and most convenient fuel to use. The amount of oxygen consumed is somewhat higher with this gas than with acetylene but the overall cost of the two gases is reduced about 30 percent in favor of propane. Propane is also much easier to control. The metal deposited with this fuel appears to be denser than when other fuels, excepting hydrogen, are used.

When hydrogen is used it should be remembered that the oxyhydrogen flame is very nearly invisible. If the flame is adjusted so there will be an excess of hydrogen, there will be less oxidization and a denser deposit.

Specific Applications

A few examples of specific applications may be of interest. When a shaft has a keyway extending into or through the section to be built up, make a dummy key so that about 1/32 in. will extend above the finished diameter. Prepare the section in the usual manner, inserting the key just before starting the spraying operation. Machine through the deposited metal and the dummy key until the finished diameter is reached. Drive the key out endwise. Do not attempt to remove it by lifting up on one end.

Pump rods and plungers that must be built up over the original diameter should have a small bead welded around each end of the metallized section. The bead should be thick enough so it will be machined along with the sprayed metal.

The preparation of crankshaft journals differs from the usual practice in that the fillets should not be under cut. Local stresses may be set up at these points if this caution is not observed. If the crankshafts are drilled for force-feed lubrication, the oil holes should be fitted with rod carbon or chalk. These rods should extend about 1/32 in. above the finished surface. After the journals are ground, the carbon or chalk can be easily removed, leaving the oil holes in the correct size and location through the hard sprayed metal.

All jobs sprayed in the lathe will have a flash built up on each end. This must be removed carefully before starting the machining operations. Use a round nose tool bit, begin at the junction of the flash and the main section, work the tool in towards the shaft and away from the sprayed section. As soon as the base metal is reached, the flash will all come off. The regular machine cut can then be taken without the danger of cracks developing in the flash and being extended into the main section by the action of the tool.

Castings that have blow holes uncovered in machining can be salvaged when strength is not involved. The area is chipped out to expose the entire cavity. Drill and tap the area on about 1-in. centers for ⅛ in. diameter headless set screws. Sandblast thoroughly and fill with a soft iron wire. Select the length of set screws so they will not extend above the finished surface. In small cavities it may not be necessary to use the set screws.

Diesel sand gas engine pistons have been reclaimed by the metallizing process for several years. No attempt is made to rebuild the ring grooves or the lands. The skirts only are rebuilt. The pistons are first heated to drive out all oil that may have been absorbed in operation. Preparation is in the lathe as outlined above. Zinc, iron, bronze, and 0.25 carbon steel have all been used in this application. The choice of metal is based somewhat on the service. Zinc is the leading metal in this application.

Cavitation in centrifugal pump casings and impellers can be repaired to restore the original efficiency of the unit and prevent further cavitation. The proper metal will depend upon local conditions, being generally stainless steel, bronze or a 13-16 percent chrome steel. The static and dynamic balance of highspeed rotating elements will not be changed if a little care is taken to deposit the same amount of metal on each vane. If it is not necessary to fill all the cavities to fully restore the efficiency, the metal can be left as sprayed. If the exact original contour is to be duplicated, the area is filled complete and an allowance is made for grinding. In most cases it is not necessary to do this.

Iron and steel parts subjected to furnace temperatures and gases generally corrode quickly. Many of these parts are now coated with either aluminum, nickel-chrome steel alloys, or straight nickel-chrome wire. Aluminum is the metal largely used for this purpose, although the nickel-chrome wire has recently been used in several large installations. The use of aluminum is recommended where the temperature is below 1800°F. If the temperatures exceed this figure, then we prefer the straight nickel-chrome alloy.

If aluminum is used, the surface is prepared by blasting and the spraying is done in the regular manner, about 0.010 in. being deposited. The sprayed surface is then covered with three successive coats of sodium silicate, allowing each coat to dry before applying the next. After the last coat has dried,

the work is placed in a furnace where the temperature is about 1500°F. and allowed to remain at this temperature for 30 min. It is then removed and allowed to cool in the air. During the heat treatment a thin coat of aluminum oxide is formed on the surface. Under this film will be a thin layer of pure aluminum. Next will come an iron-aluminum alloy, then the base metal. Some oxidization will continue in service, but the diffusion of the aluminum into the base metal will also continue.

When using the nickel-chrome alloy, the surface is not heat treated but is covered with a ceramic paint directly after the spraying is completed.

Tanks, floating roofs, and other steel structures exposed to extreme corrosion are sandblasted and coated with zinc to prevent critical loss of metal. This application will cost more than a coat of paint, but when the problem is acute it will generally prove less expensive. The sprayed zinc coat leaves an excellent surface for subsequent painting if necessary.

The examples mentioned are slightly indicative of the wide field the process covers. Many other applications will arise in the ordinary maintenance program of the refinery.

Selection of Wire

The selection of proper wire for the application in hand can be decided roughly as follows: If corrosion resistance is the main factor, stainless steel, bronze, lead, or zinc will be used, depending upon the elements causing the corrosion. Erosion or wear being the governing factor, use a hard steel such as 1.20 carbon or one containing 1 percent carbon and 2 percent chrome. If both corrosion and erosion are present, an alloy of 13-16 percent chrome steel will give satisfactory results. It is impossible to cover the selection of the specific metal for each application without knowing all the factors involved. Any metal obtainable in wire form from gold to lead can be sprayed by this process. Select the metal best suited to the conditions obtaining in the specific problem.

Because of the porous nature, grinding is the preferred method of finishing sprayed metal wherever it is possible. Excellent finishes are obtained by this method. However, all the metals that are not too hard may be finished by ordinary machine methods. The grinding of the tools and the speed and the depth of cut are factors affecting the finish. With a little experience the machinist will be able to produce good work in the lathe.

In this process, as in all others, there are a few necessary safety precautions. All low-melting-point metals are toxic in some degree when hot. Approved type respirators and masks should be worn when spraying these metals. Goggles should be worn when spraying other metals to prevent small particles from entering the eye. Workmen wearing corrective lenses should wear goggles over these lenses, as the flying particles of molten metal striking the polished surface of the lenses will stick and destroy them. When spraying inside buildings where other workmen or spectators can congregate, arrange screens or other guards so no one can get in front of the gun while it is in operation. The spray should never be directed towards the oxygen or fuel tanks, the hoses or other workmen. Proper care and lubrication of the equipment will prevent backfires in the gun itself. When more than one fuel is commonly used, the operator should be cautioned that it is necessary to change the wire nozzle to suit the fuel being used. One style nozzle will burn only acetylene, whereas the other will burn all other fuels except acetylene.

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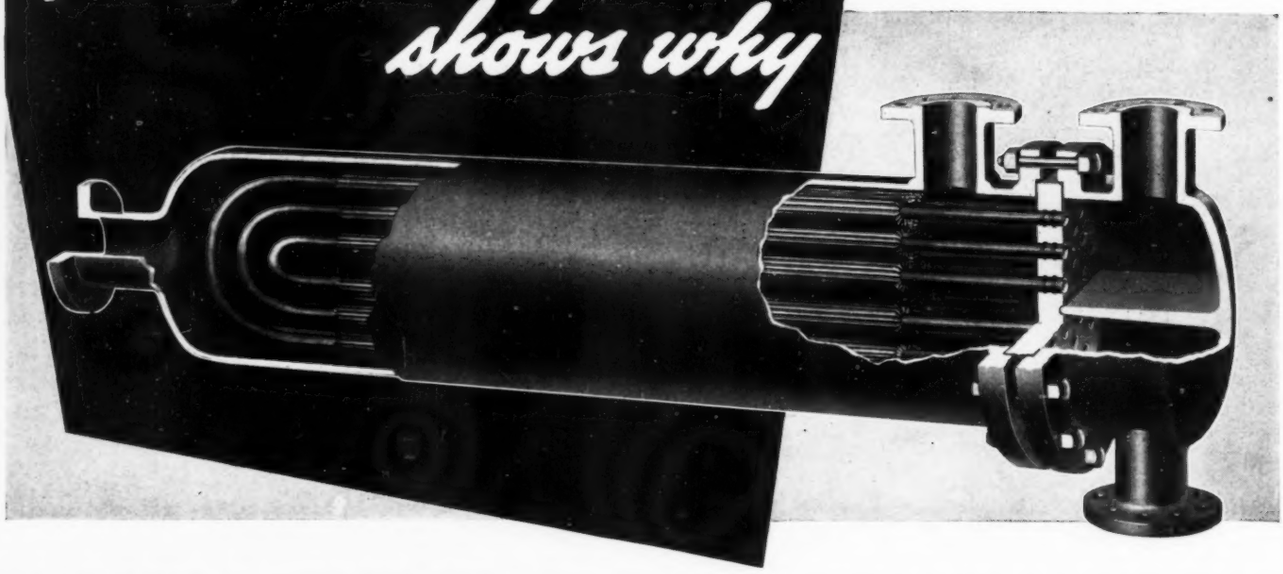

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The Effect of Vapor Load on Plate Efficiency In Fractionating Columns*

By

GEORGE GRANGER BROWN and FRANK J. LOCKHART

University of Michigan

IN the design of fractionating columns the number of plates and the column height are determined by the desired separation, the operating conditions, and the plate efficiency. The column diameter is usually determined by the allowable vapor velocity with due regard for the liquid downflow requirement.

The relation between the number of equilibrium plates, the desired separation, and the operating conditions has been discussed many times in the literature and is well understood. Although it has been recognized that column diameter as controlling the vapor load has an important effect on plate efficiency, there is not generally available any relationship that might serve as a basis for quantitative estimates of the effect of vapor load on plate efficiency. This effect may be so pronounced in many cases that economic considerations would require operation at some vapor load appreciably less than the actual limit of mechanical capacity.

This study is an attempt to determine the effect of vapor load on plate efficiency in a commercial gasoline fractionator as a means of relating the available laboratory data to commercial operations.

*Presented before American Institute of Chemical Engineers, Cincinnati, Ohio, November 16 and 17, 1942.

Column Capacity

In commercial fractionators the capacity may be limited by the inability of the column to handle liquid (priming or flooding), or by high vapor velocities causing excessive entrainment or "coning" of the liquid away from the bubble caps. The maximum amounts of liquid that can be passed downward and vapor that can be passed upward per unit time are not definitely fixed by the mechanical design and the properties of the materials being processed, but are interdependent, a change in liquid throughput affecting the maximum vapor throughput, and vice versa.[18]

In many commercial fractionators it has been found that the vapor capacity is the controlling factor determining the column capacity. As an effort to approximate the safe limits of column loading, Souders and Brown[17] suggest a maximum vapor load estimated by an empirical factor in connection with an expression derived from Stokes' Law applied to entrainment:

$$G = C\,[\rho_v(\rho_l - \rho_v)]^{1/2} \quad . \quad . \quad . \quad (1)$$

Where:

G = allowable mass velocity of the vapor, lb. per (hr.) (sq. ft.),
C = empirical factor, a function of plate spacing and surface tension,
ρ_v = density of vapor, lb. per cu. ft., and
ρ_l = density of liquid, lb. per cu. ft.

As entrainment is generally not the limiting factor in gasoline fractionation, the above equation gives values of column diameter which are quite conservative. Columns known to be operating satisfactorily show mass ve-

Fig. 1. Overall plate efficiency vs. mass vapor velocity

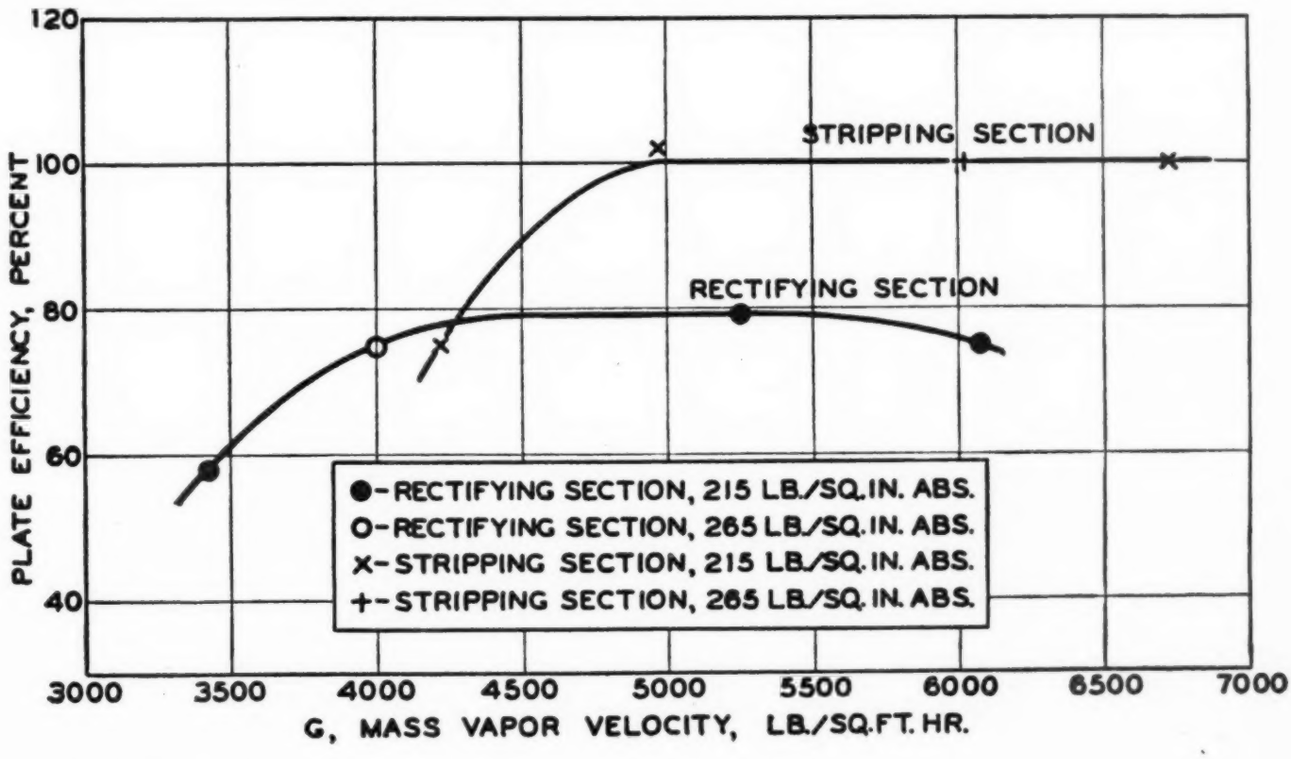

TABLE 1
Operating conditions

Pressure, lb. per sq. in. gauge	Test F		Test E		Test H		Test J	
	Test	Calc.	Test	Calc.	Test	Calc.	Test	Calc.
Tower	200		250		203		208	
Reflux Drum	190		235		195		198	
Temperatures, °F.								
Feed	188		201		238		229	
Top	125	127	147	149	128	131	133	131
Dry gas	100	107	121	127	103	107	106	110
Reflux	104	107	123	127	106	107	109	110
Feed tray	199	195	221	218	207	205	210	207
Bottoms	269	268	287	289	272	273	275	273
Reboiler Inlet	246	241	268	261	246	243	251	245
Reboiler Outlet	272		293		277		278	
Rates, moles per hour								
Feed		1118	1300	1339	783	806	1037	1063
Bottoms	665		855		476		622	
Dry gas	453		484		330		441	
Reflux	1649		1928		2841		3220	
Mole percent Vapor in feed		24		10		65		58
Reflux ratios								
L/V	0.788		0.802		0.897		0.880	
$\bar{L}/\bar{V}$	1.363		1.328		1.190		1.200	

locities 20 to 40 percent greater than that indicated by this equation.[1,14]

Based on the relatively careful analyses of an actual operating column, it has been found that this equation may also be used as a basis for estimating the effect of vapor load on plate efficiency.

Plate Efficiency

A number of individual tests giving plate efficiencies for commercial gasoline fractionators[1,3,4,7] and for oil fractionators[6,12,13,16] have been published, but data showing the effect of column loading on plate efficiency are limited and incomplete.

A natural gasoline fractionator operating at 300 lb. per sq. in. absolute pressure and at a ratio of actual mass vapor velocity to that calculated from the Souders-Brown equation (G_{act}/G_{eqn}) of 0.745 has been found to have a rectifying plate efficiency of 108 percent,[4] whereas an oil fractionator at atmospheric pressure operating at (G_{act}/G_{eqn}) of 0.60 has an overall plate efficiency of 90 percent.[13,16]

Gunness[7] reported the individual plate efficiency of a commercial gasoline fractionator as substantially constant at 100 percent between vapor velocities of 0.06 and 0.19 ft. per sec. at 255 lb. per. sq. in. absolute pressure. No efficiencies at velocities above this, which correspond to a ratio of (G_{act}/G_{eqn}) of 0.55, were given as the capacity was limited by external factors.

Carey, Griswold, Lewis, and McAdams[5] reported data on the distillation of benzene-toluene mixtures in a ten-plate laboratory column, with one bubble-cap per plate, at 16-in. plate spacing. The bubble-caps were 2 in. wide and extended entirely across the 8-in. diameter column. The efficiency was found constant at 69 percent over the range 0.2 to 2.0 ft. per sec., and to decrease gradually to 59 percent at 2.5 ft. per sec. vapor velocity. The capacity of this column was limited by lack of heating surface to a G_{act}/G_{eqn} ratio of 1.21.

Peavy and Baker[15] reported data on the distillation of ethyl alcohol-water mixtures in a three-plate laboratory column, with 10 caps per plate, at plate spacings of 6, 12, and 18 in. The plate efficiency increased to a maximum value of 120 percent with increasing vapor velocities of low magnitudes, remained constant between 1 and 3 ft. per sec. velocity, and decreased with increasing velocities above 3 ft. per sec. For plate spacings of 6 and 12 in., the reduction in efficiency with increased velocity could be satisfactorily explained on the basis of entrainment, but for the 18-in. spacing the decrease in plate efficiency was more than that estimated from considerations of the quantity of entrainment alone.

Test Data

The data used in the present computations were obtained in a series of tests made some years ago on a commercial gasoline fractionator[10] by the M. W. Kellogg Company, to whom the authors are indebted for permission to publish this study.

The column was 6 ft. in diameter, 85 ft. high, and contained 30 actual plates, with the preheated feed introduced on the tenth plate from the bottom. Plates were spaced at 30 in., with 34 bubble caps (6¾ in. diameter by 4 in. high) per plate. Each cap had 24 slots 1¼ in. high, and ⅜ in. wide at the top, and ½ in. wide at the bottom, with no skirt. Submergence (the height above the plate) was ½ in. at zero flow on all plates, due to the location of the drain holes, and at normal flow was 1⅞ in. on rectifying plates and 2¼ in. on the stripping plates. Riser area was 10.5 percent of the column cross-sectional area. Down-comers were tapered with an area 16 percent of the column area at the top and 9 percent at the lower end. Weir lengths

TABLE 2
Stream compositions in mole percent

	Test F	Test E	Test H	Test J
Reflux	*			
C_2H_6	7.10	6.80	7.71	7.03
C_3H_8	66.00	61.40	62.54	62.53
iC_4H_{10}	23.90	27.03	27.93	28.57
nC_4H_{10}	3.0	4.77	1.82	1.87
Gas				
C_2H_6	21.80	20.00	19.58	19.32
C_3H_8	66.30	64.50	68.04	66.19
iC_4H_{10}	10.93	13.77	11.64	12.82
nC_4H_{10}	0.97	1.73	0.74	1.67
Bottoms				
C_3H_8	0.15	0.	0.	0.
iC_4H_{10}	6.05	3.73	1.66	2.00
nC_4H_{10}	32.00	34.65	35.85	35.20
iC_5H_{12}	12.90	13.46	12.53	12.76
nC_5H_{12}	19.55	20.40	18.98	19.33
C_6H_{14}	12.53	11.88	13.28	13.13
C_7H_{16}	16.82	15.88	17.70	17.58
Feed†				
C_2H_6	8.84	7.24	8.02	9.10
C_3H_8	26.92	23.30	27.83	26.50
iC_4H_{10}	8.03	7.35	5.75	6.75
nC_4H_{10}	19.40	22.70	21.48	20.83
iC_5H_{12}	7.67	8.59	7.41	7.46
nC_5H_{12}	11.64	13.05	11.24	11.38
C_6H_{14}	7.46	7.59	7.81	7.69
$C_7H_{16}+$	10.04	10.18	10.46	10.29

*Calculated value in equilibrium with reported gas analysis.
†Calculated as sum of overhead distillate gas plus bottoms.

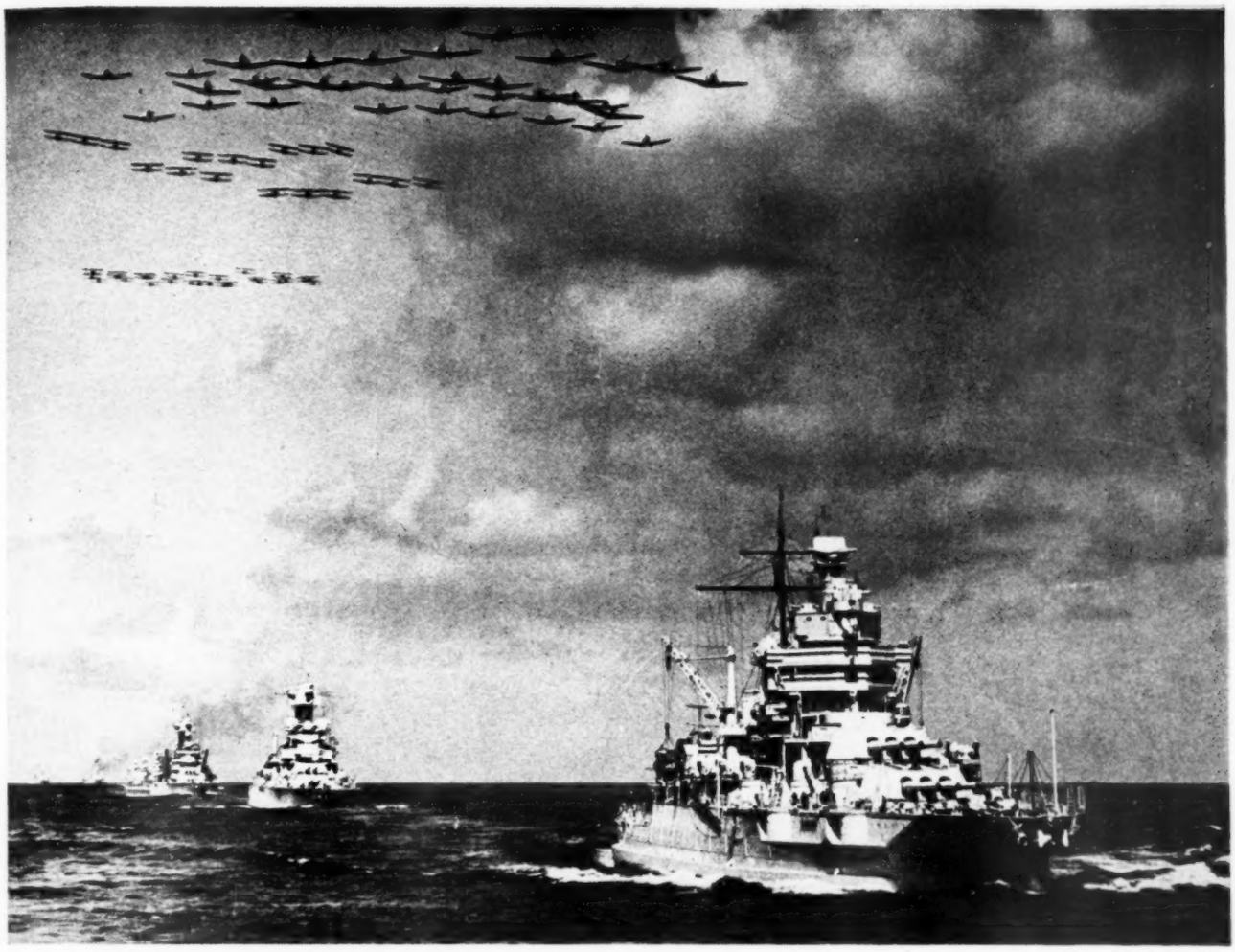

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TABLE 3

Effect of column load on plate efficiency

Test	Density, lb. per cu. ft.		Liquid overflow rate, gal. per hr.	Mass vapor velocity, lb. per sq. ft. hour		$\frac{G_{act}}{G_{eqn}}$	Plate efficiency, percent
	Liquid	Vapor		Actual	Equation		
Rectifying section (top plate temperature and pressure)							
F	30.25	2.10	20,250	3425	4700	0.728	58
E	28.50	2.55	25,520	3995	4970	0.803	75
H	29.80	2.12	35,800	5245	4660	1.125	79
J	29.80	2.12	40,700	6070	4670	1.300	75
Stripping section (reboiler temperature and pressure)							
F	30.70	2.46	45,000	4220	5420	0.778	75
E	29.40	2.99	65,100	6020	5780	1.042	100
H	30.45	2.46	44,200	4970	5400	0.921	102
J	30.45	2.46	63,200	6730	5400	1.245	100

on rectifying plates were 128 in., and on the stripping plates, 114 in.

The reflux was split, flowing past two successive rows of bubble-caps in its travel across one-half of a plate, from the sides in toward the center, down to the plate below, and outward to the perimeter on alternate plates.

Two series of tests were made, one at 250 and one at 200 lb. per sq. in. gauge pressure. The vapor rate was varied by changing the quantity of overhead reflux. Changes in feed rate were unintentional and due to changes in operation in other parts of the refinery.

In all tests the column was operated at steady-state conditions for some time, and composite samples were collected over a 6-hour period.

Temperatures of the feed, bottoms, and reflux were taken with thermometers. All other temperatures were obtained with standard operating thermocouples.

Quantities of bottom product were obtained from tank gauges. All other rates were taken from operating orifice meters.

A summary of operating conditions and analyses is given in Tables 1 and 2. The reported temperatures are probably accurate to 2°F., the pressures to within 3 lb., per sq. in., the tank gauge quantity to 1 percent and metered rates to 3 percent.

The feed stock came from cracking units and contained unsaturated hydrocarbons that were not separately determined. All analyses were reported in terms of paraffin hydrocarbons, which makes the absolute accuracy of the calculated plate efficiencies subject to some question.

Accuracy of flow rates has been verified in that all overall material balances agree within 3 percent, the metered feed being lower in all cases. Balances for individual components check poorly in some cases, probably due to uncertainties in the Podbielniak analyses as run some ten years ago.

Heat balances made around the column using the latest enthalpy data[8] were consistent with the accuracy of temperature measurement. Temperatures calculated from stream compositions and vaporization equilibrium constants[2] agree within 2°F. with the temperatures as measured at the condenser, the top plate and the reboiler in all cases.

Two methods are commonly employed for expressing the rectification performance of a bubble-cap plate, the overall plate efficiency and the individual or Murphree plate efficiency. The overall plate efficiency, defined as the ratio of the number of equilibrium plates to the number of actual plates required for the separation, is ordinarily the more convenient.

The number of equilibrium plates required for the separation in each case has been calculated by the plate-to-plate method of Lewis and Matheson.[11] By means of heat and material balances the liquid and vapor rates were computed for three plates down from the top and three plates up from the reboiler. The internal reflux ratios L/V and $\bar{L}/\bar{V}$ were substantially constant throughout each section of the column; maximum deviations from the mean values were less than 2 percent and occurred at the top plate and the reboiler. Calculations were continued to the feed plate using average values of the reflux ratios in all cases.

The overall plate efficiencies have been calculated for the rectifying and for the stripping sections of the column and are tabulated in Table 3.

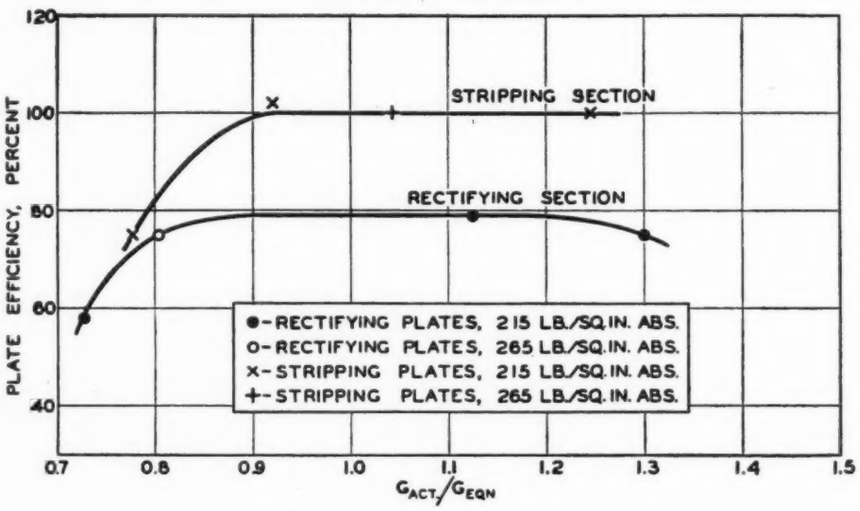
The liquid loads in gallons per hour and the vapor mass velocities have been calculated for the top plate conditions in the rectifying section and for reboiler conditions in the stripping section because of convenience. The vapor load at the top plate is very nearly the maximum vapor load in the rectifying section.

The maximum vapor loads predicted by Equation (1) have been calculated at the same places in the column, using C = 610 in the rectifying section, which corresponds to a plate spacing of 30 in. and an assumed surface tension of 10 dynes per cm., and 650 in the stripping section, which corresponds to a plate spacing of 30 in. and an assumed surface tension of 15 dynes per cm. Vapor densities have been calculated from compressibility factors, using pseudocritical temperatures and pressures as suggested by Kay.[9] Liquid densities were computed as the average of the densities of pure components at standard conditions and then corrected to the temperature and pressure.

Discussion

As this study is not concerned with the actual plate efficiency but only with the effect of column loading on the relative plate efficiency, variations

Fig. 2. Overall plate efficiency vs. vapor load



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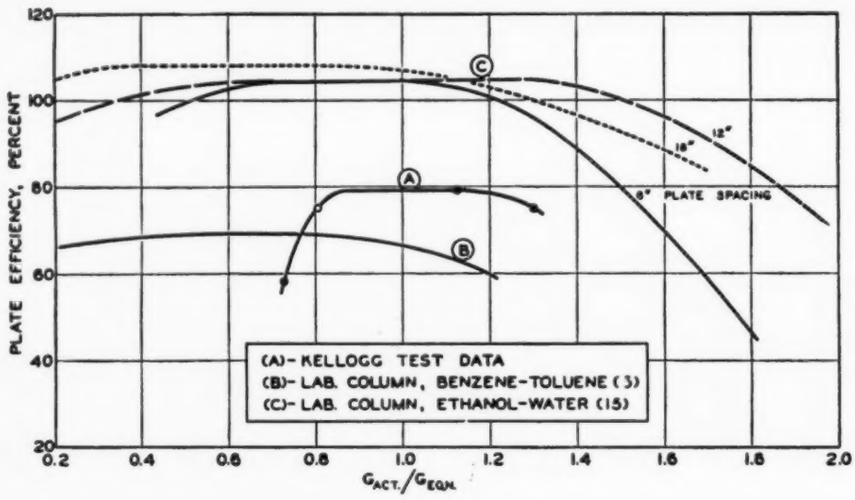

Fig. 3. Rectifying plate efficiency vs. vapor load

in plate design, spacing, and submergence are of minor consideration except in so far as they may influence the effect of vapor load on plate efficiency.

As the vapor rate was varied by changes in the pump-back reflux, the liquid downflow rate changed proportionately. Excessively large changes in liquid rates would influence the vapor-liquid contact and entrainment, but the test column apparently had adequate liquid downflow capacity as the pressure drop across the column did not change to any appreciable extent. It has been shown for laboratory columns that at the critical loading point, which depends on both liquid and vapor rates, the pressure drop increases by threefold or more.[18] No sudden or large increase in pressure drop with increased vapor rate was found in any of the tests, and the critical liquid flow was not reached. Tower operation was smooth during all tests with no apparent flooding or priming.

Overall plate efficiencies are plotted in Fig. 1 as a function of the mass vapor velocity for the rectifying and the stripping sections. At unduly low vapor rates the low plate efficiencies are probably caused by the decreased liquid level on the plates (a greater proportion of liquid flowing down the drain-holes) and channelling of the vapor due to slight differences in fluid head across the plates. At intermediate vapor velocities, within the range of normal operation, increases in vapor load correspond to increased submergence, better agitation, and longer vapor-liquid contact, but also to increased entrainment. The net result appears to be a counterbalancing of opposing factors with little change in plate efficiency over a wide range. The decreasing efficiency of the rectifying plates with higher vapor velocities is probably due to increased entrainment and "coning" of the liquid back from the caps, effectively decreasing the vapor-liquid contact.

In Fig. 2 overall plate efficiencies are plotted as a function of the ratio of the actual mass velocity to that calculated from Equation (1) for both sections of the column. Maximum plate efficiencies are obtained at or close to the maximum vapor load predicted by Equation (1). The efficiency of the rectifying plates shows a gradual decrease with higher vapor loads, whereas the efficiency of the stripping plates appears to remain constant within the limits of the data. Souders and Brown[17] point out that a greater mass velocity may be tolerated in the stripping section than in the rectifying section of the same column.

Fig. 3 shows the rectifying plate efficiencies vs. G_{act}/G_{eqn} for the laboratory columns with benzene-toluene[5] and with ethyl alcohol-water,[15] and for the present tests on a commercial column. The outstanding difference between the laboratory and the commercial columns is the abrupt decrease in plate efficiency of the latter with decreasing vapor load. This is attributed to the design of the commercial column. In both the laboratory and the commercial columns plate efficiencies reach a maximum at or close to the maximum vapor load predicted by Equation (1) and decrease gradually with higher vapor loads.

Summary and Conclusion

Based on the relatively careful analyses of a commercial gasoline fractionator and on the tests previously reported on two laboratory columns, it has been found that the overall plate efficiency is largely independent of the mass vapor velocity over a wide range of normal operation. At abnormally low vapor velocities the plate efficiency decreases very slowly in the laboratory columns and quite abruptly in the commercial column, probably due to the column design.

The two laboratory columns and the commercial column show maximum plate efficiencies at or near the maximum vapor load predicted by the Souders-Brown equation.

All of the columns studied show a gradual decrease in efficiency above this predicted maximum vapor load. In the commercial column the efficiency of the rectifying plates is constant up to a mass vapor velocity of 1.2 times the predicted maximum and then decreases at higher vapor rates. The efficiency of the stripping plates is constant to at least 1.25 times the predicted maximum vapor velocity.

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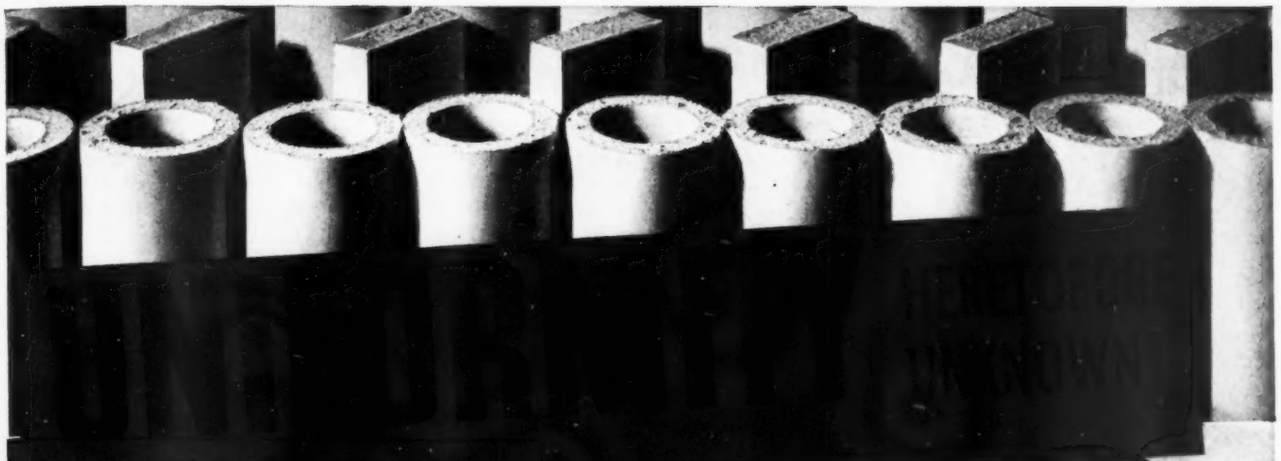

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Pumps in the Chemical Industry *

By
W. W. MELLEN and A. P. SMITH
E. I. du Pont de Nemours and Company

Historical

EXCEPT for the manufacture of sulphuric acid and muriatic acid, the chemical industry has been in existence in this country a comparatively short time; in fact, upon a large scale only for about 25 years.

During this period, its growth has been phenomenal. The number of products handled as essential materials, intermediates, and finished products has been multiplied many times. Along with this expansion, many new and complicated problems have arisen. Very prominent among these has been that of the transportation of products, either as solids or as liquids. The problem has been made more difficult by the very character of the materials manufactured. Some of these include the important acids — sulphuric, nitric, hydrochloric, and hydrofluoric, and many mixtures of them all. Also included are: caustic soda, molten lead, numerous refrigerants, intermediates for dyestuffs, a wide range of solvents, and all of the many and varied commercial organic compounds.

In the manufacture of these products, economical handling of the materials is an important part of the whole job. When conveying liquids through pipe, the methods of applying the necessary force are — gravity, compressed gases, and pumping.

Pumping problems, during the past 25 years, have been many and varied, and our present knowledge of the application of pumping equipment has been built upon the stepping stones of bitter and costly experiences. In a few instances, pumps have been designed for special application, but in general, the policy has been to purchase pumps from reliable manufacturers and to keep the choice as widely competitive as possible. In event of failure or unsatisfactory performance, the problem has been reviewed with the manufacturer. A mutual consideration of suggestions for change in design or materials of construction, has resulted in benefit, both to the chemical industry and the pump manufacturer.

When the industry was young, the number of chemicals handled was few, and there were three general types of pumps in use—the belt-driven vertical submerged type, centrifugal or turbine, the motor or belt-driven horizontal centrifugal pump with open impeller, and the steam-driven reciprocating pump.

The slow-speed, belt-driven vertical submerged type centrifugal is one of the numerous designs for special purposes. This was used very effectively and economically for circulating sulphuric acid over towers and through coolers. The design provided extra wide clearances between the casing and impeller and, although resulting in low power efficiencies, was sufficiently trouble-free to justify its use within its low head limitations.

In the effort to effect more economical operation, attempts were made to substitute manufacturer's standard centrifugal pumps for the purpose of lowering the horsepower requirement but, due to close clearances, the impeller locked because the sulphate sludge solidified when the pump was idle for comparatively short periods of time.

The motor, or belt-driven horizontal centrifugal pump with open impeller, has been used more generally. Improvements have included: revision of bearings, reproportioning of stuffingboxes, and the use of diversified materials of construction.

Reciprocating steam pumps have been used widely throughout the industry on products of all kinds. Where several of these pumps are installed, the failure of one allows quick interchange and the continuance of pumping, as reasonable change in head and suction conditions will not affect appreciably the results. Reciprocating steam pumps should be equipped with automatic lubrication.

Selection

Pumps may be selected from an almost infinite array of types as offered by the manufacturers. They may be classified into three types: the centrifugal, the positive displacement, and the air lift or jet type, the last of which is not considered in this paper. The selection of either of these types may be dependent upon any one, or all, of the following factors:

1. Corrosion
2. Erosion
3. Head and specific gravity
4. Capacity
5. Temperature
6. Viscosity

The first two items are important in determining the choice of materials, which in turn may affect the type of pump, as all types cannot be fabricated from all materials. Pumps have been fabricated from nearly every material of construction, including wood, steel, cast iron, bronze, alloy steels, silica iron, hard rubber, porcelain, glass, molded plastic, and carbon. Cast iron, bronze and steel form the standard design for ordinary service applications and usually can be treated with less regard to mechanical shock than other materials. Stoneware, glass, high silicon iron, and other brittle materials require considerable care in operation, and safeguards in the form of check valves, strainers, surge tanks and adequate suction facilities to prevent damage from water hammer and vapor binding.

When grit and solid particles must be carried in suspension through the pump, selection should be made of a design that includes wide clearances. Pumps for these services should never incorporate an internal bearing.

The usual hydrostatic and hydrodynamic factors of suction, discharge, capacity, velocity, and friction losses must be considered in computing head requirements of a pump. When pumping many of the wide variety of chemicals, specific gravity and viscosity are factors that are equally important.

Temperature is an important factor in pump application. Due consideration should be given the thermal expansion stresses likely to be encountered, as well as the characteristics of the materials of construction under the temperature conditions. The crystalline transformation point of brass or bronze usually ranges from 200 to 250°C. Pumps constructed of these materials will be fractured by surges or shocks at such temperatures. Centrifugal pumps for temperatures above 200°C. have been designed with supporting members of sufficient flexibility to permit the complete pump case to move forward as the shaft elongates or contracts, thereby protecting the impeller from damage caused by contact with the case in the direction of expansion. Materials of construction, frequently employed for high temperature work, consist of stellite or nitrited shaft sleeves, all steel casings and impellers, and high tensile alloy steel shafting. The purpose of the hardened materials in the shaft sleeves is to overcome the abrasive action of the packing, which will occur as a result of inadequate lubrication under these excessive temperatures. It is also worthwhile to consider even such a small item as the

*Presented before American Institute of Mining and Metallurgical Engineers, Boston, Massachusetts, May 11-13, 1942.

material in a casing stud bolt when the temperatures are high and the material pumped is difficult to hold. In contrast to high temperature work, cold temperatures involve consideration of resisance to shock, inasmuch as it is found usually that the tensile strength and ductility of the material is reduced appreciably as the temperature goes down. Refrigerated brines with temperatures between minus 20° and minus 70° C. sometimes are pumped in cantilever type centrifugals with high tensile alloy steel shafting to prevent breakage from thermal stresses and thermal shocks.

It is found frequently that too little attention is given the viscosity characteristics of the material. For example, a material that may be readily handled by a centrifugal pump at room temperatures, possibly cannot be handled outdoors in cold weather because of increased viscosity.

The selection of pumps for specific services, such as—for hydrochloric, sulphuric, and mixed acids, together with organic acid materials, involves consideration of the corrosion factor and, here, materials of construction are of prime importance. For pumping hydrochloric acid, hard rubber reciprocating and hard rubber centrifugal pumps have been used, but neither has been entirely satisfactory because of the brittleness of the material and its tendency to distort under temperature variation.

Centrifugal pumps made of "Durochlor" are being used extensively in handling 30 percent hydrochloric acid at temperatures from 30 to 40°C.

Early practice for pumping sulphuric acid in concentrations from 72 percent to 98 percent was to employ cast iron as the material of construction. Later, complex high chrome nickel iron alloys were substituted in place of cast iron with considerable success. For handling concentrations of sulphuric acid of 100 percent and over, cast steel is used and continues to be a satisfactory material for that purpose. In those operations where sulphuric acid is diluted to lower concentrations, or where it is mixed with other products, hard lead has been employed. More recently, however, high silicon iron for centrifugal pump construction has been utilized in this service.

Frequent experiments have failed to find a satisfactory pump for hydrofluoric acid. A small, inexpensive cast iron gear type pump with direct motor drive, having a capacity of 20 gal. per min. now is used for pumping "HF" above 60 percent in strength. Due to the high corrosive action of "HF," the pumps are replaced at frequent intervals, no repairs being attempted as the cost of these small units is low. Carbon should prove to be a very good material for use in hydrofluoric pump construction for the lower concentrations.

Mixtures of nitric and sulphuric acids, of varying compositions, are pumped with horizontal externally mounted pumps, the material of construction being high chrome nickel iron alloy. The advantages of this type of pump over vertical, submerged centrifugal pumps are ease of maintenance and the elimination of bottom bearing difficulty.

In pumping solvents, consideration must be given to overcoming the low boiling or flashing tendencies of the material. For example—low boiling liquids, such as ethyl chloride, have a tendency to flash into vapor, which often results in vapor locking. Various schemes may be employed in an effort to overcome this difficulty, such as reducing the velocity at the inlet to the pump, the elimination of obstructions in the suction lines, or the refrigeration of suction lines. Our experience indicates that an open runner multi-vane centrifugal pump, usually referred to as a turbine type pump, is advantageous on these highly volatile materials, as its characteristic is to push ahead mechanically any gases that may be present in the liquid stream, and hence the pump is kept free from vapor lock.

"Dowtherm" and diphenyl, at temperatures up to 200°C., can be pumped successfully with the rotary internal bearing type, provided systematic maintenance is carried out. These pumps are constructed of "Ni-resist" casings, mild steel rotors, bronze bushings and "Nitraloy" shaft sleeves. Maintenance experience indicates that the life of these pumps is approximately 1800 hours. When "Dowtherm" and diphenyl are circulated at temperatures above 200°C., a centrifugal pump of the cantilever type is used. These pumps have cast steel casings, cast steel impellers, high alloy steel shafting, "Nitraloy" shaft sleeves and "Nitraloy" wearing rings, if a pump of high capacity is required. If, however, a low capacity pump is needed, a "Ni-resist" or a high nickel casing should be employed because here grain growth and thermal expansion on the small size pump is an important factor that cannot be disregarded. On large pumps of high capacity, the grain growth and thermal expansion do not result in serious capacity losses. In all cases, the packing employed is diemolded of aluminum foil, and lubricated with flaked graphite.

The pump casing and packing box both are jacketed, permitting the use of steam to liquefy the material after periods of shutdown. The jacketed packing box is used for water cooling during normal operation.

Pump development usualiy results from troubles encountered with existing equipment. As an example — in pumping lead at 450°C., a standard cast iron vertical submerged pump could not be used because of grain growth. Therefore, a pump was designed having oversize shafts manufactured from high tensile strength steel. The pump column was fabricated from steel pipe, having welded steel stiffening ribs, and the column was perforated at intervals in order to equalize temperatures. Bearing surfaces were stellited. Discharge lines of 18-8 chrome nickel steel pipe were installed, and all bolts and nuts below the manhole were tack-welded. Experience has shown that these pumps operate continuously for a year, and may then be rebuilt by replacement of the shaft, impeller and bearings only.

Experiments with a graphite impregnated bushing are in progress and initial results indicate pump life will be extended 30-40 percent, when the bushing is used as a steady bearing above the liquid level.

Maintenance

The problem of pump maintenance is complicated by operating abuse as the outcome of lack of proper realization of the limitation of pumping equipment.

In order to perform satisfactory maintenance on pumps, it is necessary to have highly specialized trained mechanics for this work. At our plant, where we have approximately 2500 pumps of various types, this necessity was realized years ago and, accordingly, competent mechanics were trained through an extended period of time. These men now form the nucleus of our present force of pump repairmen.

The problem of packing is an important part of pump maintenance. When pumping volatile, toxic or corrosive materials, pumps must operate free from stuffingbox leakage. This magnifies the problem of packing lubrication and has required the introduction of special lubricants, such as graphite, mica, opal wax, castor oil, and other impregnations.

The trend toward manufacturing pumps more compactly by going to higher speeds, smaller bearings, smaller shafts and lighter casing sections has not worked out entirely successfully in a great many chemical services. It has resulted in lower initial cost, but higher maintenance cost. Particularly is this true in the combined motor pump unit, the motor bearings of which carry the entire load. Less trouble has been experienced with pumps having two bearings, or one long bearing between the stuffingbox and the motor. The anti-friction

type of bearing is favored over the sleeve type, because it is more compact and better sealed against dirt and corrosive fumes.

Stuffingbox leakage is objectionable in pumping chemicals because of the attendant hazards of explosion or personal injury, and stuffingboxes must be designed to obviate this leakage. Usually, longer stuffingboxes, which provide space for a lubrication lantern and additional packing rings, will give a satisfactory solution.

Liquid sealed stuffingboxes have been employed with satisfactory results, but the application is limited because excess sealing liquid must be collected and returned to the suction or waste.

Shaft replacement is a source of high maintenance cost due to excessive wear at the stuffingbox, particularly when corrosive materials, such as mixed acids, are pumped. Shafts made of alloy steels have longer life, but a more satisfactory solution has been obtained by hard surfacing shafts at the stuffingbox with stellite. This practice has doubled shaft life and, as a result of discussion with pump manufacturers, they now supply us from stock with hard surfaced shafts.

Analysis of maintenance cost on vertical submerged acid pumps demonstrated that the conventional brass bearing, with thrust washers, was the most common cause of failure. Replacement with anti-friction type thrust bearings eliminated these failures. Again, discusssion with pump manufacturers has resulted in their standardizing on this type bearing in their stock pumps.

Maintenance costs on horizontal belt driven centrifugal pumps with a single outboard bearing were excessive. Redesign of this type, incorporating a second outboard bearing and mounting the pulley between bearings successfully solved this problem.

Frequent failure of the conventional cast-iron or brass ball and flat type valve used in reciprocating pumps was experienced. Satisfactory solution to the problem was made by the substitution of nickel alloy steel valves, similar to the "Durabula," which, although slightly higher in price, justified their use by increasing valve life in some instances as much as ten times.

Cost Records

Experience has shown that adequate pump maintenance and resultant minimized pumping costs can be obtained when a preventive maintenance program is established. An inspection service was instituted at our plant by selecting skilled pump repairmen and assigning them to periodic pump inspections. These "inspector mechanics" oil, grease, and make minor adjustments to pumping equipment, the frequency of which is based on experience. Maintenance cost analysis has indicated expenditures have been at substantially the same level in 1941, a period of high production, as they were in other years of low production, even in face of higher labor rates. We believe our system of pump inspections has contributed to this satisfactory performance.

Pump inspections consist of a visual examination of the exterior of the pump. If there is evidence of stuffingbox leakage, packing glands are adjusted or packing replaced. Points of lubrication are checked and lubricants added if necessary. No dismantlement is attempted, but a check is made for wear or vibration and should there be evidence that bearings or shafts require replacement, a shutdown period is arranged. These inspections enable pumps to operate at long periods and, therefore, the continuity of operation is not interrupted with too frequent shutdowns.

These inspections also disclose work of a nature that cannot be handled by the inspector on his regular rounds. His work, of necessity, is limited to small jobs of a servicing nature. Where larger repairs are required, they usually can be foreseen sometime in advance. In such cases, a standard completely analyzed work order is prepared and the work is scheduled at the earliest convenience of the production department.

Pump repairs may be divided into two categories. One consists of that job which may be done without removal of the pump from its location, and the other where the pump must be sent to a central shop for reconditioning. Most pumps are repaired in the field, if replacement parts may be easily transported there, and installed within a short period of time. Where continuity of operation is absolutely necessary, a spare unit is on hand for immediate installation.

The basis of our cost control system is the standard analyzed work order that is used to initiate all repair work. In the maintenance of pumps, as in the maintenance of any other equipment, some system must be available to allow the maintenance engineer to have at his immediate disposal the accumulated expenditures against any specific piece of equipment. An equipment cost record system to provide for the accumulation of such information is in use at our plant.

All equipment, including pumps, has been assigned an equipment number, and a card has been established for each unit. On the completion of each maintenance job, the date, a brief description of the work, including a list of all replacement parts and material used, together with material costs and labor charges, is recorded on the card.

This record permits the maintenance engineer to determine quickly expenditures against any unit. Where the ratio of maintenance expenditure to initial cost is found to be excessive, investigations are undertaken to determine methods of lowering expenditures. These studies may result in the substitution of a more suitable material of construction or a change in design, or both.

These equipment cost records have proved that periodic pump inspections are an important phase of field maintenance practice. From this system, we were able to determine that, for an increase in production of 100 percent, the increase in pump maintenance costs in locations where pump inspections were not provided, was four times as great as in comparable locations where pump inspections had been established.

It is apparent that appreciable savings can be realized through the adoption of pump standards for the purpose of minimizing the multitude of pump types that are procurable. These standards simplify and reduce maintenance costs. We think these standards should be based on the types outlined here for specific services, and that they should be purchased from a few reputable manufacturers. Standardization of pumping equipment will make the purchasing and stocking of special parts easier and will require less investment. The degree of special training necessary for pump mechanics will be reduced.

The observance of these three factors, namely, proper selection, preventive maintenance by periodic inspections, and the thoughtful analysis of cost records, should lighten the burden of pumping problems in the chemical industry.

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Prediction of Suction Limitation When Pumping Volatile Liquids *

By
CLARK D. BOWER and PERRY H. BROWN
Joshua Hendy Iron Works, Pomona Pump Company Division

THE handling of gasoline by pump manufacturers who in the normal procedure of their business are concerned with the pumping of water is something relatively new and can be attributed primarily to the increased demand for aircraft to conduct the war. The preliminary study of the problem of pumping gasoline indicated that enough work had been done to predict accurately the performance of the pumping equipment as to head, capacity, and horsepower from previously known water performance. There seemed to be no published information, however, on the suction limitations of such pumping equipment when handling gasoline.

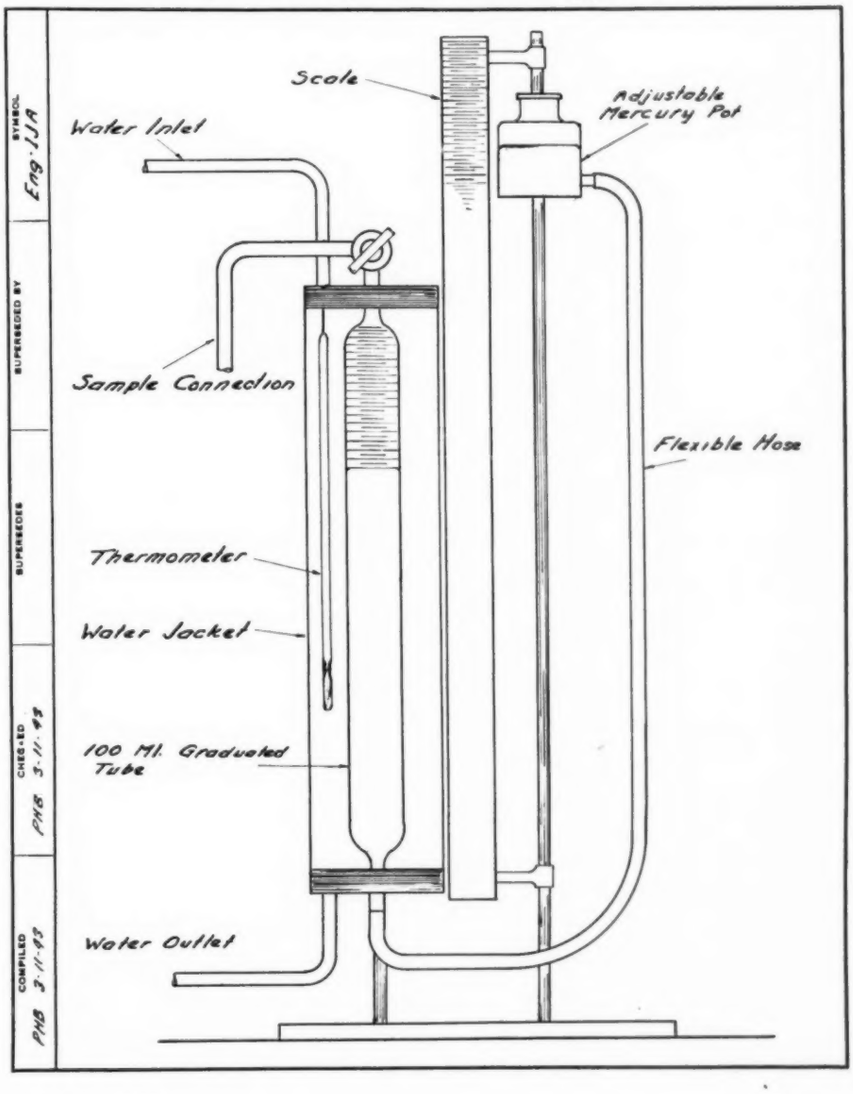
The Pomona Pump Company decided that tests to obtain the cavitation characteristics of pumps pumping gasoline were in order and if these tests could be properly correlated through the vapor characteristics of the fuel to be pumped to the water cavitation characteristics, it would then be unnecessary to test each pump in gasoline. Our first objective of testing one pump in gasoline was relatively simple and was conducted in the usual manner of obtaining the suction limitations for various head, capacity, and speed conditions. This information was obtained in the same test set-up for both 100-octane gasoline and for water.

The test set-up consisted primarily of a re-circulation system where a storage tank of 800 gal. was connected to the suction of the pump. The discharge head was obtained by throttling, the capacity measured by a venturi meter, and the suction head, which could be varied from positive to negative gauge values, was measured by a mercury U-tube. Power input to a calibrated motor was obtained by an indicating wattmeter that aided materially in the detection of cavitation. Temperature control was obtained by cooling the tank, and readings of the temperature of the fluid were taken at regular intervals in pump suction.

For purposes of discussing the results, it becomes necessary to refer to suction head as a positive suction head above absolute zero and to neglect the use of the terms suction head as being pressures above atmospheric and suction lift to being pressures less than atmospheric. It is necessary, of course, in making cavitation tests to measure suction lift or suction head as gauge reading converted to suction head above absolute zero when the barometric pressure is known.

It was found that a correlation of the results could be obtained between the gasoline tests and water tests when reduced to certain basic values. To establish this correlation between the two, it becomes necessary to determine the minimum NPSH required to keep the pump in cavitation-free operation. To determine the minimum NPSH as applied to this test it is necessary to obtain the minimum values of the absolute suction head under cavitation-free operation, which itself is calculated from the barometric pressure minus the suction lift. By subtracting the vapor pressure of fluid being pumped at a given temperature from the absolute suction head the minimum NPSH, or what we had designated as suction factor, is obtained. The suction factor similar to other characteristics of flow within the pump remains constant for a given speed and head and capacity condition for pumping fluids of the same low viscosity. Therefore the suction factor as obtained by pumping water in feet of water is the same for pumping gasoline in feet of gasoline for the same pumping conditions. By going di-

Fig. 1. Bubble point determination apparatus



*Presented before California Natural Gasoline Association, April, 1943.

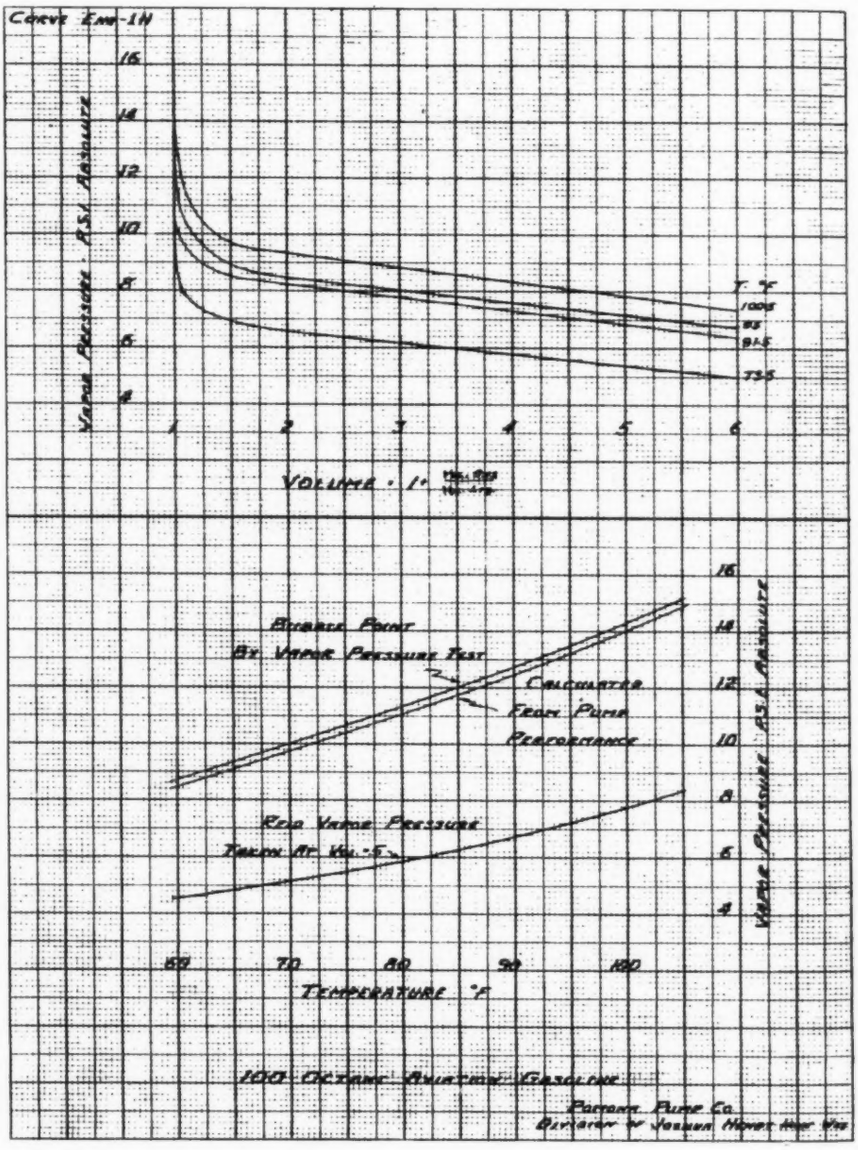
rectly to the tests and determining the suction head at which the pump would operate for the same conditions of service in both gasoline and water, it was found that the pump, when handling gasoline, required a great deal more suction head to operate cavitation-free than when pumping water. This was as expected. Therefore, we had four factors involved in comparing the two tests, the suction factor of the pump and the vapor pressure of the liquid for pumping both gasoline and water. As we knew the suction factor to be the same for gasoline and water and could obtain the vapor pressure of the water, we were able to calculate what we originally termed the apparent vapor pressure of 100-octane gasoline.

When plotting this curve of the apparent vapor pressure with the vapor-pressure temperature curve for 100-octane gasoline as obtained from the refinery, we discovered a great deal of disagreement between these two curves. The values of the apparent vapor-pressure curve were greater than the vapor-pressure curve obtained from the refinery, being greater by amounts from 4½ lb. at 70° to 7 lb. at 100°. This was disturbing as it did not check our original premise or lend aid in trying to correlate the established vapor-pressure characteristics of water and gasoline. We continued our tests by testing an enclosed runner pump and two Westco turbine type pumps, and from these tests obtained further confirmation of these apparent vapor-pressure curves by the same method of analysis. These results, however, did give us the information needed to accurately predict suction limitations for handling 100-octane gasoline, assuming, of course, that there would be a similarity between all blends of 100-octane gasoline with the same Reid vapor pressure.

These results were still not satisfactory and we wished to carry the work further in order to establish the proper characteristics of the gasoline, which would enable us to make accurate predictions regarding gasoline suction limitations from our previously established water suction limitations. In checking with the refineries and discussing the problem with various persons, it was found that the vapor-pressure temperature curve that we had received from the refineries had been obtained from tests with a Field apparatus in which the vapor volume is approximately four times that of the liquid volume. Cavitation, as detected by small decreases in capacity from the normal head capacity curve, we now felt to be the manifestation of vapor pressure under conditions of limited vapor space. This gave a new interpretation of vapor pressure. Characteristics of the fluid under cavitation conditions presented a logical course to follow for further analysis. As a result of this interpretation, we first built a small vapor bomb in which we attempted to limit the volume of vapor space and measure vapor-pressure temperature characteristics under these conditions. The results obtained from this apparatus were quite erratic but did indicate that as the vapor space was decreased, the vapor pressure at a given temperature was increased.

Because of this lack of ability to measure accurately the vapor pressure-temperature relationship under conditions of varying vapor volume, we contacted Dr. Sage. Through him we obtained information regarding the proper type of apparatus with which to measure this apparent vapor pressure. Drs. Sage and Lacey have previously conducted many tests with an apparatus of this type to determine the bubble point of hydrocarbons and have written a book, "Volumetric Phase Behavior of Hydrocarbons," covering this work. The bubble point is that point on the pressure-specific volume diagram below the critical state where vaporization begins at a constant temperature. With this information at hand, we proceeded with the construction of a bubble point apparatus and conducted a series of tests in an attempt to correlate what we had previously called our apparent vapor-pressure curve to a series of bubble points as obtained from the bubble point apparatus. The agreement between these two curves is quite remarkable; however, first let us describe the apparatus (Fig. 1). The apparatus, as used for the experiment, consisted simply of the gas measuring tube with an adjustable mercury reservoir. The gas measuring tube was jacketed by a glass cylinder through which water could be circulated and in which a ther-

Fig. 2. Total volume-vapor pressure relationship at constant temperatures



A LESSON IN WATER COOLING

LESSON 4 OF A SERIES

INTERNAL "FILLING"

A prime essential to the efficient performance of many cooling towers is the wood "filling." This is the latticework arrangement of close-set horizontal slats or bars which occupies the greater portion of the tower's interior from the water distribution system at the top to the catch basin at the bottom.

The purpose of the filling is to mix mechanically the falling water with the moving air so as to facilitate the transfer of heat. In most cases the water, showered or sprayed evenly over the top level of the filling, splashes downward from one level to the next by gravity while the air moves either horizontally or vertically through the falling water by means of natural or mechanical draft.

Utmost exposure of water surface to passing air is thus accomplished by repeatedly arresting the water's fall, splashing it into fine droplets, and spreading it into thin films. The filling should also maintain a uniform fall of water over the entire area at all levels and permit the free passage of adequate air volume to absorb and carry off heat rapidly.

A well-designed cooling tower filling embodies the following features in such a manner as to give optimum results:

Maximum horizontal splashing surface
Maximum active wetted surface
Minimum restriction to air flow
Freedom from warping, buckling and sagging
Maximum structural strength
Maximum ease of removing and re-installing
Minimum of nails, bolts or other metal

TOTAL HEAT CONTENT OF AIR AT VARIOUS WET BULB TEMPERATURES

at Standard Barometric Pressure

W.B. Temp. °F	BTU per Pound	W.B. Temp. °F	BTU per Pound	W.B. Temp. °F	BTU per Pound
		54	22.55	78	41.42
30	**10.89**	56	23.77	**80**	**43.51**
32	11.73	58	25.05	82	45.72
34	12.56	**60**	**26.37**	84	48.05
36	13.41	62	27.76	86	50.47
38	14.28	64	29.21	88	53.02
40	**15.19**	66	30.73	**90**	**55.70**
42	16.13	68	32.31	92	58.52
44	17.11	**70**	**33.96**	94	61.50
46	18.12	72	35.70	96	64.62
48	19.16	74	37.51	98	67.92
50	**20.25**	76	39.42	**100**	**71.40**
52	21.38				

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← *Short Spans Prevent Sag - All Battens Stay Level and in Precise Alignment Permanently - Even Water Distribution From Top to Bottom*

← *A New High in Structural Strength*

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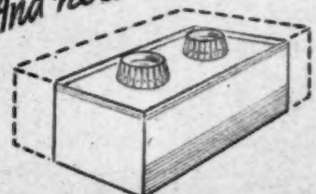

Smaller Size Tower For a Given Duty **OR** Lower Water Temperatures From a Tower of Given Size

MARLEY

COOLING TOWERS THE MARLEY COMPANY INC. KANSAS CITY, KANSAS

mometer was suspended. The sample of chilled gasoline was siphoned into the gas measuring tube by lowering the mercury reservoir. By agitating the tube while raising the mercury reservoir, an air-free sample of gasoline of approximately 20 cc. was trapped in the tube. Water was then circulated through the jacket until a constant temperature was obtained. With the mercury reservoir raised high enough so that the sample remained in a liquid state, the mercury reservoir was slowly lowered, until a few bubbles of vapor formed above the liquid. The sample was agitated and a record made of the vapor volume, total volume, temperature, and pressure. By lowering the mercury reservoir still further and taking readings for different values of vapor volume, a curve of the total volume-vapor pressure relationship at constant temperatures was obtained (Fig. 2).

On the curve, we have arbitrarily set the liquid volume as unit volume and plotted the total volume as equal to the liquid volume, plus the volume of vapor, divided by the volume of liquid. The bubble point is that point at which the vapor-pressure curve for a given temperature intersects the coördinate representing unit volume. With patience, the bubble point can be found quite accurately with the apparatus used as the initial vapor volume in the apparatus is confined to that portion of the gasoline measuring tube just below the cock. The bore of the tube where the first small amounts of vapor are confined is approximately 3/32 in. in diameter whereas the bore of the tube in general is approximately ¾ in. in diameter.

By plotting a series of bubble points on a temperature-vapor pressure curve, we obtained the upper curve. From the cavitation studies of pumping both water and gasoline as previously outlined, a second curve shows the vapor-pressure temperature relationships as obtained by that method. The third curve shows an approximate curve that might be obtained by the Reid method, obtained by plotting the vapor-pressure relationships for volume five of the previous vapor pressure-volume curves.

As can be seen from the curves, there is very close agreement between the bubble point and the apparent vapor pressure for a given temperature; whereas the Reid vapor pressure and the apparent vapor pressure were in wide disagreement. Within the accuracy of the test equipment, we could for all intents and purposes say that the bubble point and apparent vapor pressure describe the same limiting vapor pressure necessary to evaluate the cavitation limitations in pumping gasoline.

We cannot assume this to be entirely true, however, as there are minor modifying limitations between the measurement of the bubble point by the apparatus and the detection of bubble point in pump cavitation. There is primarily the time element; that is, the apparent vapor-pressure values could be slightly modified from the bubble point by the extremely small lapse of time during which the gasoline is exposed to the low pressure of the maximum suction velocity. This is true as it takes a certain amount of time for the vapor pressure-liquid volume relationship to reach equilibrium. This would result in the apparent vapor pressure having a value equal to the vapor pressure at a volume slightly larger than one for a given temperature. Attributing the difference between the bubble point and the apparent vapor pressure for 100-octane gasoline to this factor alone, the vapor volume would be taken at values between 1.01 to 1.02.

Secondly, the slope at which the vapor volume-vapor pressure curve approaches the unit volume coördinate, or liquid state, would have a very definite bearing upon the detection of cavitation in pumping. If this curve approaches the liquid state at a very acute angle, the agreement between bubble point and the apparent vapor pressure as found by cavitation tests will not be as good as when the curve approaches unit volume at a greater angle. The detection of cavitation in general cannot be made to the degree of accuracy with which the bubble point can be determined. We believe that the limiting vapor pressure, or that vapor-pressure value to be used to assure cavitation-free operation, is found by the bubble point method.

If the bubble point is appreciably higher than the vapor pressure at vapor volumes slightly larger than one, however, it should be considered practical to use as a limiting vapor pressure the vapor pressures up to relative volume 1.05. It must also be remembered that a slight increase in temperature or a reduction in barometric pressure might result in serious cavitation if no margin of safety has been allowed in the initial determination of pumping conditions. The use of any vapor-pressure designation other than bubble point to describe the fuel to be pumped when determining the pumping conditions may lead to serious operating difficulties.

We feel that the application of bubble point method to suction limitation prediction for pumping equipment is entirely practical. Although we have established the use of bubble point to correlate the water with 100-octane gasoline cavitation studies, further work should be done to include other blends. For the present time, however, this work is not being carried forward at the Pomona Pump Company due to the pressure of the war business. It is hoped that at some future date when world affairs are in better shape that we can continue with this study and perhaps obtain as a part of the pump's specification from refineries buying gasoline pumps the bubble point for the particular conditions at which they expect to have the pumps operate.

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War Has Speeded Research

The motorist of the future instead of buying a new set of tires for his car may buy a new car for his tires, in the opinion of Dr. Gustav Egloff, director of research of Universal Oil Products Company. This is because the tires will be made of synthetic rubber, designed by man to meet exact specifications and produced from petroleum in American refineries. The new metals and alloys and new techniques of using them, however, will make the car far more durable than have been the models of the past, so it may become a race against time between cars and tires.

Dr. Egloff points out that the spur of war has speeded up research so that more has been accomplished in the last two years than had been achieved in 50 prewar years. In his opinion, the greatest developments are to come in the field of airplane and automobile production, which in turn are dependent on the production of suitable fuels and lubricants by the petroleum industry, which has also advanced by giant strides since the beginning of the war, and is still increasing.

Materials of construction cited as having been discovered, developed, or greatly improved since the beginning of the war are magnesium, aluminum, and their alloys, plastics, plywood, and glass.

The development of the synthetic rubber industry in the war is showing us how to make ourselves independent of foreign sources of supply and to make rubber available at low cost for a vast number of uses to which it has not yet been applied. As examples of this are cited a thorough cushioning of railroad cars, better insulation of train bodies, and the silencing of unnecessary noises from many sources.

Present-Day Furnace Design*

By H. O. JOHANSON
M. H. Detrick Company

THE manufacturers of suspended walls and arches are playing an important part in the present-day design of furnaces as the suspended walls and arch constructions are one of the main component parts of any furnace.

Wall and arch manufacturers have not only provided considerable materials and assistance in furnace design to the refining industry, such as represented here, but also play a major role in supplying materials and assisting with the design and construction of furnaces for the manufacturing, steel, shipping, utility, smelting, and many other industries.

Suspended walls and arches have already proved, in your own plants, that they greatly reduce or eliminate the five main reasons for troubles and failures of refractories, namely, melting, softening, spalling, fluxing, or expansion. As this is an established fact, no further discussion is necessary as to the details and features of suspended construction.

The trend of suspended wall and arch construction is still taking the same path it started on a few years ago, that is, reduced tile thicknesses for the low temperature furnaces. We can all very readily understand that a tube still furnace, which is a low temperature furnace, should not use the same suspended wall and arch construction that a steel mill furnace, boiler, or heavy-duty high temperature furnace.

Sound engineering principles proved that it required less castings and less steel to carry the lighter and thinner refractory thickness, and also proved that with a small increase in the thickness of insulation used to back up the refractory, a construction with a greater overall efficiency was obtainable.

The 3-in. and 4½-in. tile depth walls met with some resistance only a few years ago, but are now well accepted and considered standard construction by many engineers and tube still designers. The thin wall, as it is commonly known, from the economical, engineering, and operating standpoints, lends itself very nicely to tube still design due to its simplicity, flexibility, low cost, ease of erection, and saving of materials.

The tube stills of today are carefully considered from all angles, and the selection of the proper suspended wall is always given due consideration. The furnace temperature and conditions are analyzed and a wall of proper refractory thickness is selected. The value of the fuel and the minimum heat loss desired is then considered, which sets the required thickness of insulation to back up the suspended walls.

In the past, casings of some sort, namely, steel plate, transite, or red brick were installed on nearly all tube stills; however, present-day practice, due to the inability to procure and necessity to save, has all but eliminated the above casings.

Casings have been replaced in most cases by a hard finish material that is a part of the suspended wall. This hard finish material of approximately 1-in. thickness is installed on the outside of the insulation and forms a permanent outside casing for the furnace. The hard finish material has proved itself as a casing where severe climatic conditions are encountered. This casing has been accepted by the powers that be as a substitute for steel plate casing, especially for the duration.

A suspended wall and arch is made up of refractories, castings, and steel, and you may be interested in the restrictions placed on these three items.

Theoretically, no priority is needed for suspended wall and arch tile and refractories; however, from the practical standard, an A-1-A is required in order for the refractory companies to secure materials for dies, molds, and repairs, and to make shipment.

Suspended wall and arch manufacturers are able to obtain raw materials to handle 50 percent of A-1-A priority rating or better; 35 percent A-1-D or better, and 15 percent of A-10 or better. This, however, is expected to be changed at a very early date. The fact is, as of October 1 we were unable to get copper on less than A-1-A, which means that no Mechanite castings can be procured on less than A-1-A rating.

No structural steel is obtainable on a priority rating less than A-1-A, and we believe this may be revised upward if the volume of A-1-A priority is greater than the existing volume. There are some who think that priorities are going to be a thing of the past. Some who seem to know a little about it are looking for allocations of all steel.

We have mentioned insulation in connection with suspended walls, and the priority situation in regard to insulation is very similar to that mentioned for refractories.

On many of the present-day tube stills and boilers we have noticed that radial brick or concrete stacks are being used to save steel plate wherever possible, and along this same line we have noticed that more and more boilers are being installed with induced-draft equipment to conserve steel plate normally used for breechings and tall stacks.

There has been a constant call for good used boilers, and many old boilers are being moved and reset today. With modern settings these boilers are producing more steam than ever before and the manufacturers of suspended walls and arches have played a big part in modernizing the old boilers. I believe the War Production Board has charge of all the used boilers, and they are allocated much like other commodities or requirements.

One of the most recent problems that the suspended wall manufacturers have been asked to face, and to assist with the details, is the lining of the catalytic regenerator vessels, and the piping in connection with the vessels. Experiments on refractories and the engineering in connection with the design are now going on. We can all rest assured that the wall manufacturers will develop a trouble-free lining for these vessels and piping the same as they have in the past developed linings for all light- and heavy-duty furnaces.

That concludes my prepared paper, but I might take a little time to tell you about some of our problems in designing present-day tube stills. We are not allowed to use any more alloy than is absolutely necessary, and if our catalyzation shows that alloy is absolutely necessary, say for intermediate support, then we have to get permission to use even this little amount of alloy. Wherever possible we are saving steel and are saving alloy in favor of meehanite. If meehanite is too good, we use cast iron. We reduce the thickness of the refractories to the lowest minimum to conserve castings to support the wall, and the steel supporting structure is now figured from the book with allowance for the safety factor, rather than as in the past, when stills were designed for appearance's sake. If a 6-in. I-beam would do the job, and it wouldn't look good, we used to use 8 or 10. Now, if 6 will do the job, we use the 6.

We do the same things with boiler plants. We are keeping down everything to a minimum. Walkways, if they are needed, are being put in; if they are not needed, or if we can get by without them, they are not being put in.

We would all like to have automatic plants, with automatic controls, and a power house that would just run like a clock, but in times like these it is impossible to get such controls. Up to a certain point, they are putting in the controls that are needed; and those that are not, are not being put in.

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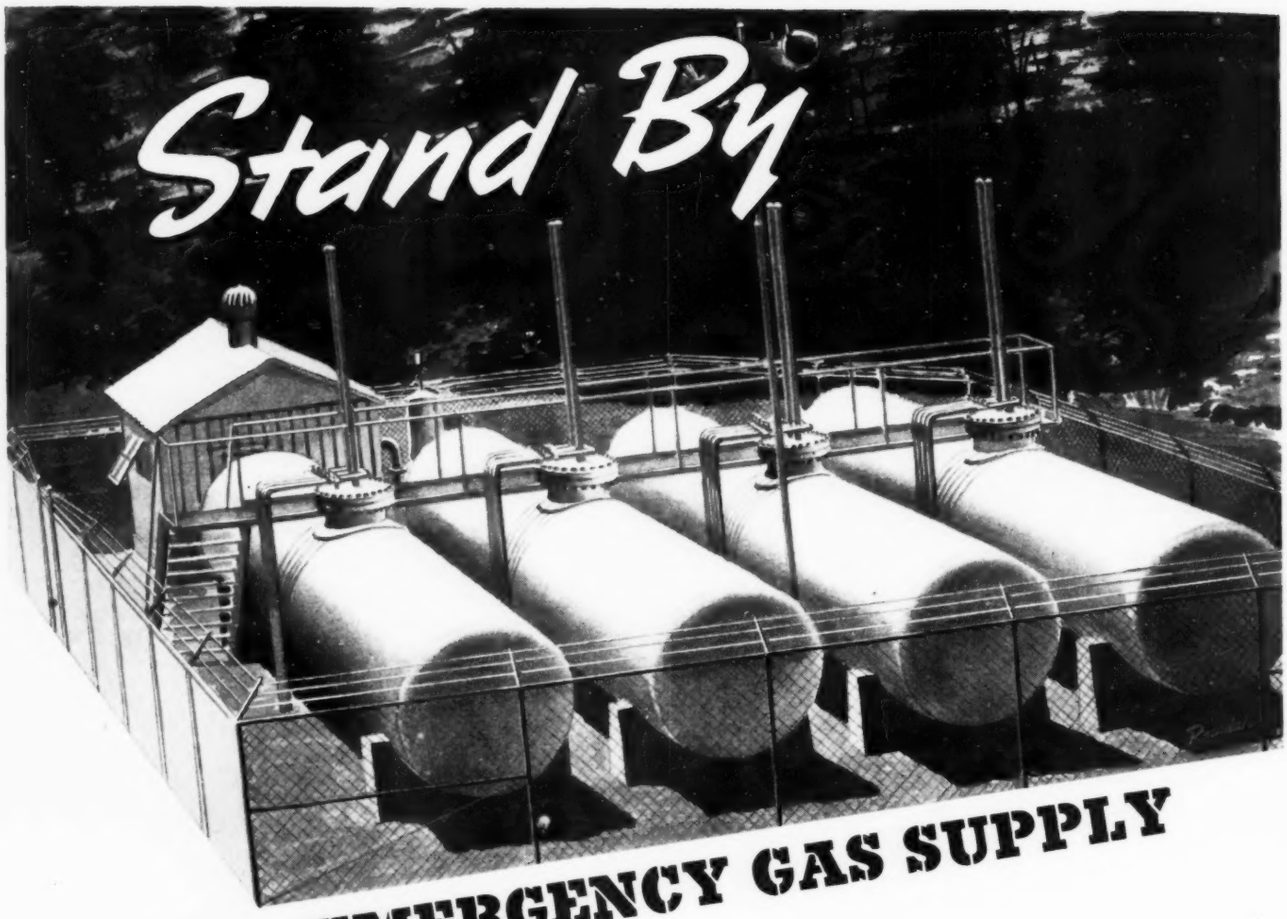
*Presented before Western Petroleum Refiners Association, Wichita, Kansas, October 9, 1942.



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Method of Analyzing the Gasoline Fraction of Petroleum, With Preliminary Results on East Texas and Oklahoma Crudes*

By

FREDERICK D. ROSSINI,** BEVERIDGE J. MAIR†, ALPHONSE F. FORZIATI,‡
AUGUSTUS R. GLASGOW, JR.‡ and CHARLES B. WILLINGHAM‡

Abstract

THIS paper gives a general description of a method for analyzing the gasoline fraction of petroleum with respect to the main hydrocarbon components. The results of a test experiment on a mixture of 17 known hydrocarbons (6 paraffins, 4 naphthenes or cycloparaffins, and 7 aromatics) normally boiling in the range from 60 to 174°C., are presented, together with preliminary results on the naphtha fractions from East Texas and Oklahoma crude petroleums.

Introduction

For about 15 years A.P.I. Research Project 6 has been exhaustively separating one crude petroleum, by distillation, extraction, adsorption, and crystallization, and to date has separated a total of 69 hydrocarbons from the gas, gasoline, and kerosine fractions, together with a large number of "homogeneous" fractions from the lubricant portion.[1,7] The knowledge of the hydrocarbons in petroleum obtained in this comprehensive investigation is providing a basis or framework by means of which less extensive and more rapid analyses of other crude petroleums can be made to yield, with regard to the hydrocarbon constituents, information that otherwise would not be obtainable.

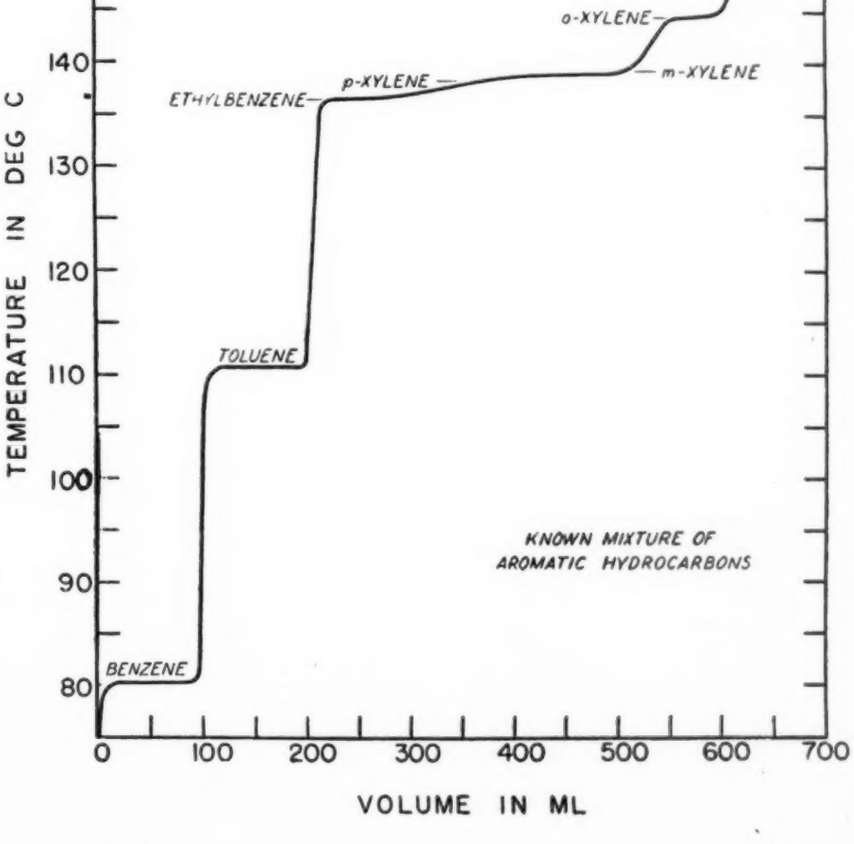
In 1941 the Advisory Committee§ for A.P.I. Research Project 6 recommended that a survey be started by the project on the analysis of the gasoline fraction of representative crude petroleums from various fields. All of the experience and knowledge gained in the comprehensive investigation on the one crude petroleum was to be brought to bear on this new problem, in order to bring forth in a relatively short time fruitful information on the hydrocarbons in the gasoline fraction of the selected petroleums. Within the last year the project has developed a method of analysis for this work that it is hoped will have application beyond the bounds of the present investigation. This paper briefly describes the method, and gives some preliminary results on East Texas and Oklahoma crudes.

Description of Method

The method consists essentially in applying the fractionating processes of adsorption and distillation to the naphtha fraction. The process of adsorption is used to separate from the naphtha fraction a portion containing the aromatic hydrocarbons and a portion containing the paraffins and naphthenes. Then the process of distillation is used to resolve each of these two portions separately.

By adsorption, the naphtha is first separated into two portions: one containing the aromatic hydrocarbons, together with the non-hydrocarbon components; and the other, the paraffins and naphthenes. From the first portion, the small amount of non-hydrocarbon components (principally sulphur compounds) are separated by further adsorption to give a clean aromatic portion. Then the clean aromatic portion and the paraffin-naphthene portion separately are subjected to an analytical distillation at a high reflux ratio in a column of high efficiency and low hold-up. The boiling point of the distillate is observed as a function of its volume. The distillate is collected in fractions as small as practicable, and the refractive index of each fraction is determined. When necessary for further identifica-

Fig. 1. Plot of the boiling point as a function of volume for the distillation (at a controlled pressure of 770 mm. mercury) of the aromatic hydrocarbons from the known test mixture



*Presented before American Petroleum Institute, Chicago, Illinois, November 9-12, 1942.

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TABLE 1

Approximate operating characteristics of the two analytical distillation columns

Designation of still	"O"	"P"
Rectifying section:		
Diameter, mm.	10	13
Length, mm.	1830	1830
Packing	Stedman	Heli-Grid
Operating throughout (liquid), ml. per hour	About 150	About 250
Operating holdup (liquid), ml.	About 25	About 30
Operating pressure drop, mm. of mercury	18	10
Reflux ratio	120 to 1 150 to 1	120 to 1 150 to 1
Rate of removal of distillate (liquid), ml. per hour	1	2 to 2½
Nature of charge	Aromatic	Paraffin-naphthene
Volume of charge, ml.	600	3600
Time of distillation, hours	600	1600
Pressure, mm. of mercury	770	770

TABLE 2

Analytical data on the test mixture of 17 known hydrocarbons before and after processing

Compound	Boiling point, °C.	Percentage by weight of charge	Percentage by weight of product	Difference, percent
2-Methylpentane	60.3	3.30	3.58	+0.28
*n*Hexane	68.7	5.56	5.10	−0.46
Benzene	80.1	4.94	5.10	+0.16
Cyclohexane	80.8	9.08	8.86	−0.22
*n*Heptane	98.4	7.59	7.82	+0.23
Methylcyclohexane	100.9	8.08	7.99	−0.09
Toluene	110.6	5.37	5.26	−0.11
*n*Octane	125.6	6.03	6.10	+0.07
Ethylcyclohexane	131.8	3.55	3.58	+0.03
Ethylbenzene	136.2	4.99	4.59	−0.40
*p*Xylene	138.4	5.11	10.51	+0.32
*m*Xylene	139.2	5.08		
*o*Xylene	144.4	4.22	4.16	−0.06
*n*Nonane	150.7	6.31	6.11	−0.20
*Iso*propylbenzene	152.4	5.98	6.39	+0.41
*n*Propylcyclohexane	156.7	6.58	6.65	+0.07
*n*Decane	174.0	8.23	8.20	−0.03
Total		100.00	100.00	
		Average difference		±0.20

tion, the density is determined (by combining two or more adjacent fractions, if necessary).

The determination of the main hydrocarbon components in the respective aromatic and paraffin-naphthene portions is based upon a comparison of the boiling point, refractive index and, when necessary, the density of the fractions of distillate with those of appropriate pure compounds.

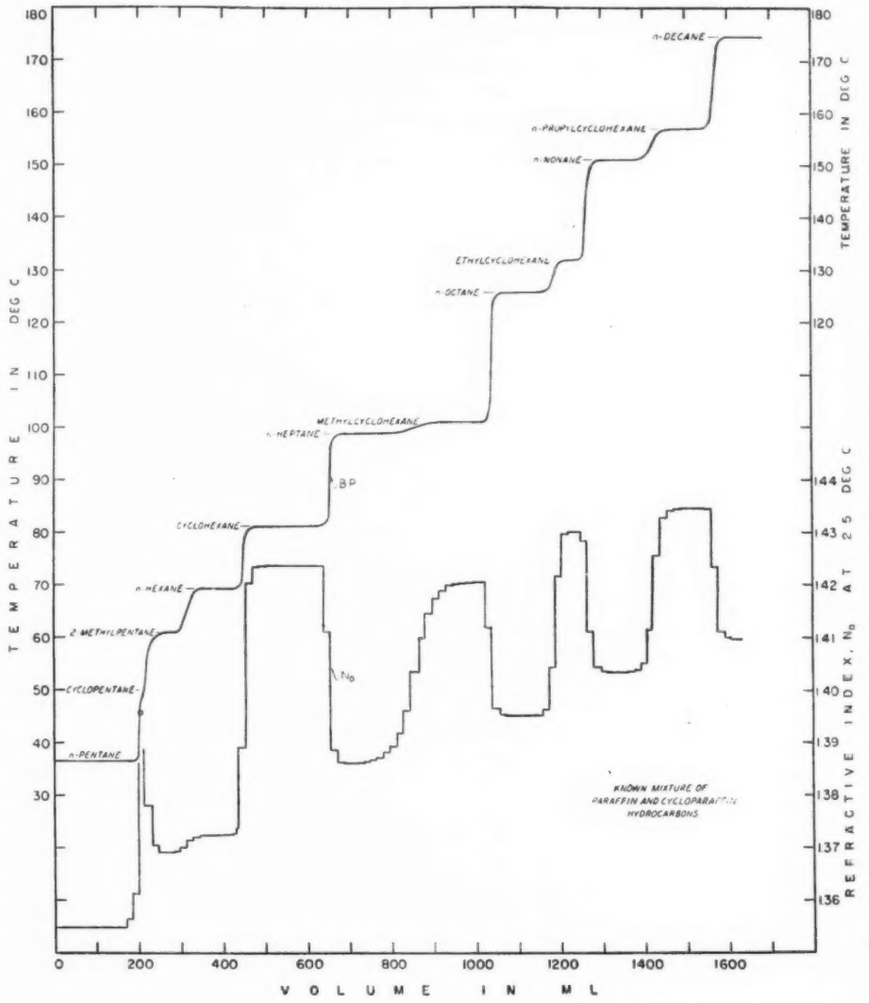
It is important to note that the distillation of the aromatic hydrocarbons separately from the paraffins and naphthenes, as outlined hereinbefore, not only makes much easier the determination of the main aromatic compounds, but also immensely improves the resolution of the main components in the paraffin-naphthene portion. This improvement results partly from the reduction in the number of compounds in the mixture being distilled, but mainly from the fact that the relations of vapor pressure and temperature are much more homogeneous for the aromatic portion and for the paraffin-naphthene portion separately than for the original mixture of the two portions.

The separation of the naphtha into an aromatic portion and a paraffin-naphthene portion by the process of adsorption requires only one or two days, depending upon the amount of aromatics to be separated. On the other hand, the analytical distillation of the two separated portions may be made to require as little as two or three days, or as much as two or three months, depending on the extent to which the resolution by distillation is to be carried; i.e., the time required for the analysis of naphthas by this method will vary from about one week per naphtha for a routine method wherein it is desired to obtain sufficient information for the intelligent immediate utilization of the material in plant processing, to two or three months per naphtha for a research method wherein it is desired to learn as much as possible about the individual components of the material from the standpoint of long-range planning for its utilization.

Procedure of Investigation

In the present investigation the amount of the naphtha selected for processing is such as to produce not less than about 600 ml. of an aromatic portion and not less than about 3600 ml. of a paraffin-naphthene portion. Then each of these two portions in the amounts stated is subjected to an efficient analytical distillation. The distillate is collected in fractions of 6 ml.,

Fig. 2. Plot of the boiling point and refractive index as a function of volume for the distillation (at a controlled pressure of 770 mm. mercury) of the paraffin and naphthene hydrocarbons from the known test mixture



each representing about 1/100 of the aromatic portion and about 1/600 of the paraffin-naphthene portion. For each fraction, determination is made of the refractive index, N_D. When necessary for further identification, two consecutive fractions are combined for measurement of the density, by means of a specific-gravity balance that requires a minimum volume of 10 ml. and which has a precision of ± 0.00003 gram per ml.

The process of adsorption used in the present investigation to separate and recover the aromatic hydrocarbons from the paraffins and naphthenes is an improved modification of that described in earlier papers of the project.[2,3] The new procedure is given in detail in a recently completed report[4] of the project which, during the war period, is available for restricted distribution to the American Petroleum Institute and U. S. government laboratories and, on application, to other appropriate groups. As mentioned in the preceding section, the small amount of sulphur and other non-hydrocarbon compounds, which in the first adsorption are separated with the aromatic hydrocarbons, then are removed (together with a small amount of aromatic hydrocarbons) from the "aromatic" portion by further adsorption to produce a clean aromatic portion for distillation.

The analytical distillations of the aromatic and the paraffin-naphthene portions obtained in the present investigation are being performed in the two columns whose operating characteristics are given in Table 1. Still "O" is being used on the aromatic portion and still "P" on the paraffin-naphthene portion. The assembly, testing, and operation of these rectifying columns will be described in a separate publication.[5] As can be seen from the data given in Table 1, the time required for the distillation of the aromatic portion is nearly one month, with continuous operation 24 hours per day, seven days per week; and the time required for the distillation of the paraffin-naphthene portion is more than two months with similar continuous operation. By such distillation it is possible to separate effectively a considerable number of individual components in one distillation.

In the distillation of the aromatic portion (see Fig. 5, for example) each of the eight possible aromatic compounds normally boiling below 160°C. can be resolved with the exception of *p*xylene and *m*xylene, which normally boil only 0.8°C. apart near 139°C. Fortunately, however, the composition of the mixture of *p*xylene and *m*xylene can be determined readily from a measurement of its freezing point.* Above

*The freezing points are +13.2°C. for *p*xylene, and −47.9°C. for *m*xylene.

TABLE 3

Assay distillation (Engler) of the East Texas light and heavy naphthas (data provided by the Standard Oil Development Company)

Light naphtha (depentanized)		Heavy naphtha	
Percentage	Temperature, °F.	Percentage	Temperature, °F.
Initial	136	Initial	248
2.5	158	2.0	257
37.0	176	7.0	266
77.0	194	27.5	284
98.0	212	47.0	302
Final	216	62.5	320
		74.0	338
		82.5	356
		90.0	372
		91.0	374
		96.0	392
		Final	399

160°C., the number of possible aromatic compounds increases rapidly, and the extent of the analysis which is possible will depend upon the number of close-boiling neighbors, and upon the difference in their refractive indices and densities.

In the distillation of the paraffin-naphthene portion (see Fig. 4, for example) it is likewise possible to resolve a number of individual components in the one distillation. Excluding *cis*-1,2-dimethylcyclopentane near 99°C., *cis*-1,3-dimethylcyclopentane near the same temperature, 2,2,3-trimethylbutane at 80.9°C., and 2,2,4-trimethylpentane at 99.2°C. — no one of which has yet been found in any petroleum† — there are 20 possible paraffin and naphthene (cyclopentane and cyclohexane derivatives) hydrocarbons normally boiling in the range from 40 to 102°C. These are as follows:

Compound	Type	Boiling point, °C.	
Cyclopentane	Naphthene	49.5	B
2,2-Dimethylbutane	Paraffin	49.8	
2,3-Dimethylbutane	Paraffin	58.0	A
2-Methylpentane	Paraffin	60.3	A
3-Methylpentane	Paraffin	63.3	A
nHexane	Paraffin	68.7	A
Methylcyclopentane	Naphthene	71.9	A
2,2-Dimethylpentane	Paraffin	79.0	A
2,4-Dimethylpentane	Paraffin	80.8	B
Cyclohexane	Naphthene	80.8	
3,3-Dimethylpentane	Paraffin	86.0	A
1,1-Dimethylcyclopentane	Naphthene	87.5	A
2,3-Dimethylpentane	Paraffin	89.8	
2-Methylhexane	Paraffin	90.0	
trans-1,3-Dimethylcyclopentane	Naphthene	90.9	C
trans-1,2-Dimethylcyclopentane	Naphthene	91.9	
3-Methylhexane	Paraffin	92.0	
3-Ethylpentane	Paraffin	93.5	A
nHeptane	Paraffin	98.4	A
Methylcyclohexane	Naphthene	100.9	A

†It is likely that every petroleum contains at least a minute amount of nearly every possible paraffin, naphthene, or aromatic hydrocarbon. Fortunately, however, the bulk of the gasoline fraction of Mid-Continent petroleum, and to a greater or lesser extent other crudes, is made up of a relatively small number of compounds.[1] If found in petroleum in any significant amount, the two *cis*-dimethylcyclopentanes mentioned previously likely would appear in a naphtha very rich in naphthenes, and the two trimethyl paraffins in a naphtha very rich in isoparaffins.

A distillation column having a separating efficiency near 120 theoretical plates can effect a separation of 2 hydrocarbons normally boiling as little as 1.5°C. apart. One distillation in such a column of a mixture containing all of the foregoing 20 components would yield the following results: the 11 compounds marked "A" would be substantially separated as individual components; the 2 pairs marked "B" would be binary mixtures each containing a paraffin and a naphthene hydrocarbon of about the same boiling point, the relative amounts of which could be determined readily from the refractive index or density or both; the mixture of 5 hydrocarbons marked "C" would not be resolvable in the one distillation, but the relative amounts of paraffins and naphthenes could be determined readily from the refractive index and density. It is interesting to note that all of the 20 hydrocarbons listed previously herein have been isolated from petroleum[1,8,9] with the exception of the following four compounds: 2,4-dimethylpentane at 80.8°C.; 3,3-dimethylpentane at 86.0°C.; 2,3-dimethylpentane at 89.8°C.; and 3-ethylpentane at 93.5°C.

Testing the Method

In order to establish the reliability of this method of analysis, and to learn something of the amount of loss of material in processing, a test mixture of 17 known hydrocarbons, normally boiling in the range from 60 to 174°C., was prepared quantitatively by weight. The mixture had a volume of about 2.3 liters, and consisted of 6 paraffin, 4 naphthene, and 7 aromatic hydrocarbons.

This mixture was separated by the process of adsorption into two lots: one containing the aromatic hydrocarbons, and the other containing the paraffins and naphthenes. Each lot then was subjected to an analytical distillation. An indication of the completeness of the separation, and of the amount of material lost during the processes of adsorption and distillation, is given by the following summary.

Material	Aromatics	Paraffins+naphthenes	Total
Charged	624.91 grams 35.69 percent	1,126.01 grams 64.31 percent	1,750.92 grams 100.00 percent
Recovered	617.71 grams 35.28 percent	1,099.66 grams 62.80 percent	1,717.37 grams 98.08 percent
Loss	7.20 grams 0.41 percent	26.35 grams 1.51 percent	33.55 grams 1.92 percent

If the amounts of aromatics and of paraffins plus naphthenes lost in the two fractionating processes are approximately in the same ratio as their percentages in the original mixture, the composition of the material recovered will be, on a percentage basis, the same

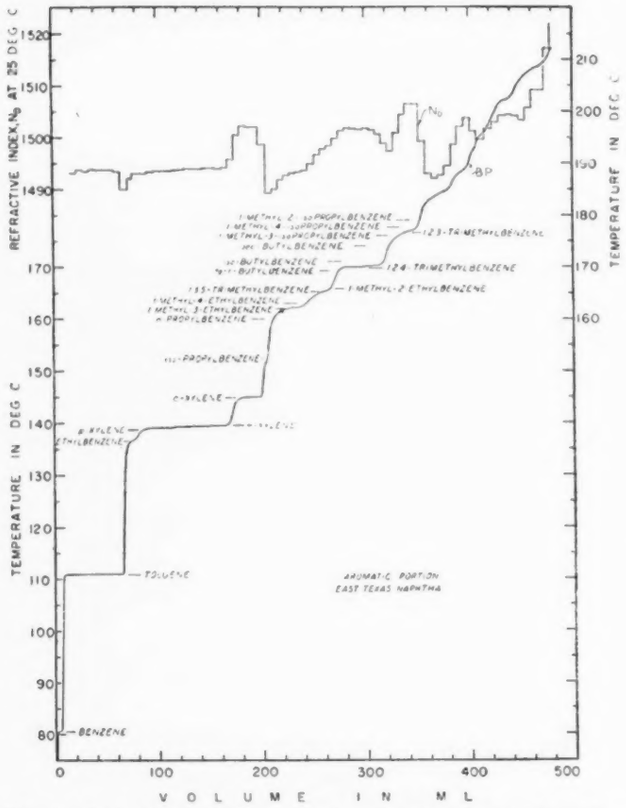


Fig. 3. Plot of the boiling point and refractive index as a function of volume, for the distillation (at a controlled pressure of 770 mm. mercury) of the aromatic hydrocarbons from the East Texas naphtha

For reference, the boiling points of all the possible aromatic hydrocarbons normally boiling below 180°C. are indicated. The data represented here, plus a determination of the freezing point of the mixture of *p*xylene and *m*xylene, will serve readily to determine the amounts each of benzene, toluene, ethylbenzene, *p*xylene, *m*xylene, *o*xylene, *iso*propylbenzene, and *n*propylbenzene. Above 160°C., the number of possible aromatic compounds increases rapidly, and the analysis with respect to individual compounds becomes more difficult and less certain.

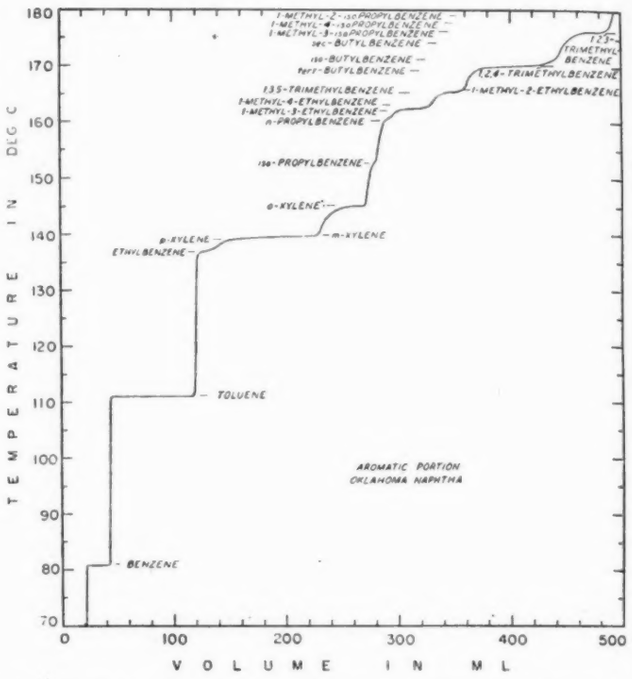
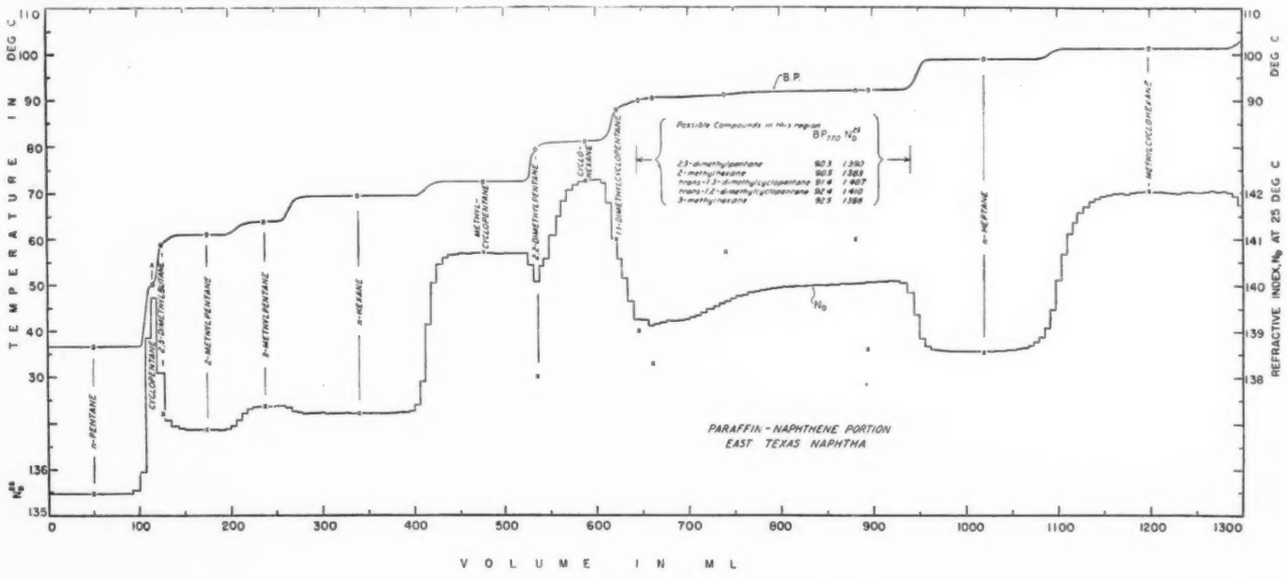


Fig. 5. Plot of the boiling point as a function of volume, for the distillation (at a controlled pressure of 770 mm. mercury) of the aromatic hydrocarbons from the Oklahoma naphtha

For reference, the boiling points of all the possible aromatic hydrocarbons normally boiling below 180°C. are indicated. The data represented here, plus a determination of the freezing point of the mixture of *p*xylene and *m*xylene, will serve readily to determine the amounts each of benzene, toluene, ethylbenzene, *p*xylene, *m*xylene, *o*xylene, *iso*propylbenzene, and *n*propylbenzene. Above 160°C., the number of possible aromatic compounds increases rapidly, and the analysis with respect to individual compounds becomes more difficult and less certain.

Fig. 4. Plot of the boiling point and refractive index as a function of volume, for the distillation (at a controlled pressure of 770 mm. mercury) of the paraffin and naphthene hydrocarbons from the East Texas naphtha

At the time this plot was made, the distillation was about one-third completed. The circles and crosses represent, respectively, the boiling points (at 770 mm. mercury) and the refractive indices (n_D at 25°C.) of the indicated compounds in the pure state. The data represented here will serve readily to determine the amounts each of *n*pentane, cyclopentane, 2,3-dimethylbutane, 2-methylpentane, 3-methylpentane, *n*hexane, methylcyclopentane, 2,2-dimethylpentane, cyclohexane, 1,1-dimethylcyclopentane, *n*heptane, and methylcyclohexane. It is seen that the material of the range 90 to 93°C. (at 770 mm. mercury) is complicated by the presence of several close-boiling paraffin and naphthene compounds.



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as that of the material charged. The extent to which this was true in the foregoing experiment is indicated by the following figures giving percentages by weight:

Material	Aromatics (percent by weight)	Paraffins+ naphthenes (percent by weight)	Total (percent by weight)
Original	35.69	64.31	100.00
Product	35.97	64.03	100.00
Difference	+0.28	−0.28	

Because the distilling columns described in Table 1 had not yet been assembled, the two portions of the test mixture were distilled separately in a column with the following operating characteristics: rectifying section 15 mm. in diameter and 2800 mm. in length; operating throughput, 750 ml. of liquid per hour; separating efficiency at the operating throughput, near 110 theoretical plates; operating holdup, about 75 ml. of liquid; reflux ratio, 120. The values of boiling point and refractive index of the distillate, as a function of its volume and mass, showed in the case of both portions excellent accord with the known composition of the material.

Fig. 1 gives a plot of the volume-temperature relation for the distillation of the aromatic portion. Fig. 2 gives a similar plot for the paraffin-naphthene portion, together with a plot of the refractive index as a function of the volume of distillate. The appropriate compounds are indicated on the charts. Table 2 compares the known composition of the material charged into the adsorption process with the analysis of the product from the distillation process.

Preliminary Results on East Texas Naphtha

The East Texas naphtha was provided by the Standard Oil Development Company. Batch-distillation data on the crude petroleum were reported by them as follows:

	Percentage of crude (by volume)	Aniline point, °F.	Gravity, °A.P.I.
C_4 fraction	0 to 1.0	...	....
C_5 fraction	1.0 to 3.3	...	....
Light naphtha	3.3 to 14.3	128	66.6
Heavy naphtha	14.3 to 38.8	126	50.8

Data on the Engler distillation for the light and heavy naphtha are given in Table 3. For this investigation, the "dependanized" light naphtha and the heavy naphtha were combined in the production proportion of 11.0 to 24.5, by volume, to make the total East Texas naphtha for analysis. The material examined represented 35 percent by volume of the crude petroleum. By a method[6] developed recently in the work of A.P.I. Research Project 6, the amount of aromatic hydrocarbons in this East Texas naphtha was found to be 10.4 percent by volume. The sulphur content of the naphtha was 0.033 percent by weight*

In the manner previously described, the naphtha was separated into an aromatic portion and a paraffin-naphthene portion. The aromatic portion was distilled in still "O," which is described in Table 1. Fig. 3 shows the boiling point and the refractive index of the distillate from the aromatic portion as a function of its volume. The paraffin-naphthene portion is being distilled in still "P," which is described in Table 1. Fig. 4 shows the boiling point and the refractive index of the first part of the distillate (to 103°C.) from the paraffin-naphthene portion as a function of its volume. Although the data have not yet been reduced to final form, the following approximate figures will give an indication of the amounts of some of the hydrocarbons in this East Texas naphtha, in percentage by volume:

Benzene	0.1	Cyclopentane	0.3
Toluene	1.3	2,3-Dimethylbutane	0.3
Ethylbenzene	0.4	2-Methylpentane	2
*p*Xylene }	1.6	3-Methylpentane	1½
*m*Xylene }		*n*Hexane	4
*o*Xylene	0.6	Methylcyclopentane	3
*Iso*propylbenzene	0.1	2,2-Dimethylpentane	0.2
*n*Propylbenzene	0.1	Cyclohexane	2
		1,1-Dimethylcyclopentane	0.2
		*n*Heptane	4
		Methylcyclohexane	5

Preliminary Results on Oklahoma Naphtha

The Oklahoma naphtha being analyzed is from the original Mid-Continent petroleum that has been under extended investigation by the project. The assay properties of this petroleum have been given previously.[7] For this investigation, a naphtha fraction was made by taking that part of the crude coming over as distillate between 46 and 180°C. in a column of nearly 100 theoretical plates operated at a reflux ratio of about 15 to 1. This portion represented 35 percent by volume of the original petroleum. The aromatic content of this naphtha was found to be 9.8 percent by volume, and the sulphur content 0.017 percent by weight (see preceding section).

As before, the naphtha fraction was separated into an aromatic portion and a paraffin-naphthene portion. The aromatic portion was distilled in still "O." Fig. 5 shows the boiling point of the distillate from the aromatic portion as a function of its volume.

Crudes to Be Analyzed

In addition to the East Texas and Oklahoma crudes described in this paper, which are intermediate in type, the Advisory Committee has selected the following crudes as next to be analyzed by this method:

Type	*Field*
High aromatic	Conroe, Texas
High paraffin, low naphthene	Greendale-Kawkawlin, Michigan
High *iso*paraffin	Winkler, Texas
High naphthene	Midway, California
High paraffin, low aromatic	Pennsylvania

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*Determined under the supervision of R. C. Hardy in the Section on Lubrication and Liquid Fuels at the National Bureau of Standards.

A Refiner's Viewpoint on Motor Fuel Quality*

By

W. M. HOLADAY and JOHN HAPPEL

Socony-Vacuum Oil Company, Inc.

SINCE 1915 the automobile industry has developed rapidly until there are now some 32,000,000 motor vehicles registered in the United States. The major proportion of this equipment is powered by gasoline engines, and in order to operate these engines the petroleum industry must produce more than a million and a half barrels of gasoline a day.

One has merely to lift the hood of a car to visualize the complexity of an automobile engine. The complexity of the fuel, although not so obvious, is equally great. An automobile engine may have on the average 2000 different parts. The hydrocarbon compounds that compose a gasoline may amount to about the same number. The task of identifying these compounds, isolating them, and determining their effect on internal-combustion engine operation is stupendous, and only a start has been made in this direction. As fast as the results of such investigations become available, they are being applied to the manufacture of gasoline. The need for increasing quantities of higher quality fuel has resulted in the adoption of new refining processes almost as soon as they are developed in the laboratory.

It is the purpose of this paper to describe some of the processes now used in manufacturing gasoline, and to show how they are applied to make this highly specialized product.

Gasoline Characteristics

Before proceeding to a description of refining processes, it will first be desirable to review briefly the various properties of a good gasoline. As will be seen, not all these properties are subject to close control by the refiner. Furthermore, the refiner is faced with the problem of producing an adequate amount of fuel at a reasonable price. However, the requirements of modern automotive engines are of major importance in the control of gasoline characteristics.

The nature of the fuel used in an engine affects performance, economy, and in many cases, the durability of mechanical parts. Judging from customer reactions and complaints, the average car owner is most interested in performance. Satisfactory performance includes smooth, knockless operation and full power output, freedom from vapor lock at summer temperatures, rapid warmup in cold weather, easy starting, and good acceleration. Good economy involves a minimum consumption of fuel while retaining desirable performance characteristics. To insure low maintenance costs, freedom from gum formation and corrosive action, together with minimum tendency toward dilution of crankcase oil are important.

From the point of view of fuel formulation, control of octane number, vapor pressure, and distillation are of major importance. Quiet operation is obtained in any given engine by supplying it with a fuel of sufficiently high knock rating to avoid detonation. Freedom from vapor lock is insured by proper control of vapor pressure. Ease of starting, proper warmup, good acceleration, and freedom from excessive crankcase dilution are controlled by distillation characteristics. These are the major items subject to refinery control.

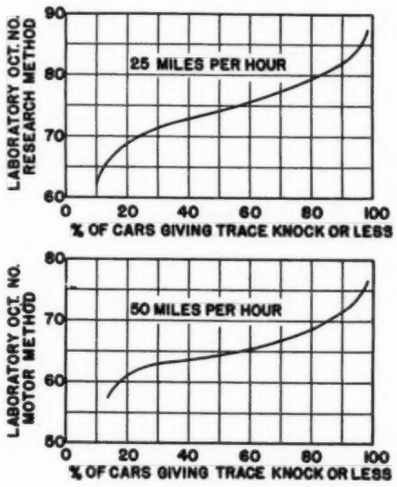


Fig. 1. Comparison of octane numbers and road performance

There are also several items that pertain to the long time reliability of a fuel and its effect on engine condition. Excessive amounts of gum in gasoline may cause such troubles as sticking valves and clogged fuel passages. A high sulphur content is undesirable in gasoline because in the presence of moisture, the exhaust gases can produce acids that may cause corrosion. All reliable refiners produce gasolines that are well on the safe side in these respects, as the cost of satisfactory control of gum and sulphur content is in most cases small when compared to the other items mentioned.

Fuel Economy

The subject of fuel economy deserves special comment. With a car performing satisfactorily in other respects, there is very little that the refiner can do about mileage. In general, fuel consumption depends on the thermal efficiency and the heat of combustion per unit weight of fuel. In the case of gasoline, variation in heat of combustion per unit weight is very small, so that the fuel consumption in miles per pound will remain practically constant. Based on this premise, a simple rule can be derived, that for fuels in the gasoline range, an increase of 3° A.P.I. in gravity will result in a decrease in miles per gallon of about 1 percent. It is not possible for the refiner to exercise much control over gasoline gravity except by decreasing overall volatility or by increasing the percentage of aromatics. The use of a very low volatility gasoline would result in the loss of starting, warmup, and acceleration performance, whereas the inclusion of sufficient aromatics to affect gravity appreciably is precluded by cost considerations as well as by some aspects of performance. In other words, the refiner finds that other factors than mileage control the formulation of gasoline.

Variations in fuel consumption caused by differences in driving habits, traffic conditions, and, of course, by the mechanical condition of the car are far greater than can be accounted for by fuel composition. Such effects have been amply covered by other investigators, and it is needless to discuss them at this time.

Preparations containing aniline, naphthalene, and other anti-knock agents are also sold in various attractive containers with extravagant claims of added mileage. At the prices charged for the anti-knock improvement obtained, it would be far more economical to purchase a gasoline of suitable octane number as manufactured by a reliable refiner.

Anti-knock Quality

Turning again to those qualities of gasoline to which the refiner must pay particular attention, one of the most important is anti-knock value. Most changes in engine design today tend to-

*Presented before Society of Automotive Engineers, Annual Meeting, Detroit, Michigan, January 16, 1942.

ward higher compression ratios with consequent improvement in efficiency and power output. In most cases, however, such changes result in increased knocking tendencies owing to the higher operating pressures thus produced. Improvements in engine efficiency have, therefore, been somewhat dependent upon the fuels of higher knock ratings.

To properly evaluate anti-knock requirements, the refiner must refer to road anti-knock quality and its relationship to anti-knock quality as indicated by laboratory control methods on his particular fuel. The road octane number test method now in favor was adopted following tests at San Bernardino in 1940 by the Coöperative Fuel Research Committee.[1] Although insufficient data have been obtained by this method for a rigorous analysis of the influence of speed on knocking characteristics of all types of gasolines, the treatment of road octane values at low speed (25 m.p.h.) and a higher speed (50 m.p.h.) makes it possible to give some indication of fuel behavior under two important driving conditions. The values obtained for the 25 m.p.h. speed are indicative of knocking under the moderate conditions encountered in metropolitan and suburban traffic. Values indicated for 50 m.p.h., which, like the lower speed figures, are for full throttle acceleration, apply to more severe driving conditions such as cross country, hilly country, or heavy-duty commercial operation.

By combining the road octane number vs. speed curves with data on passenger car octane number requirements, it is possible to evaluate fuel ratings in terms of the percentage of cars satisfied at various speeds. Data on typical commercial gasolines would indicate that fuels having the same laboratory Research Method[2] octane number will satisfy very nearly the same percentage of cars at speeds in the neighborhood of 25 m.p.h. and fuels having the same Motor Method[3] octane number will satisfy very nearly the same percentage of cars at speeds in the neighborhood of 50 m.p.h. As low speed acceleration is of predominant importance in most areas, the Research Method octane number is a very satisfactory basis for octane number specification.

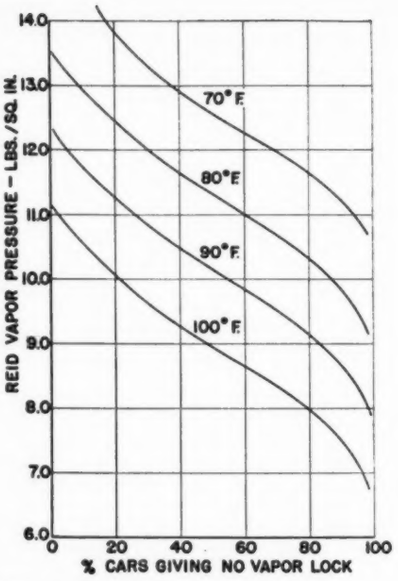


Fig. 2. Passenger car vapor pressure requirements at various air temperatures

Fig. 1 gives a correlation between the two laboratory octane numbers and the percentage of cars satisfied at 25 and 50 m.p.h. This plot is intended as a guide to show how laboratory inspections may be used in a general manner to control the anti-knock quality of gasoline to given performance standards. It is realized that published work of other investigators has indicated the effects of such factors as octane number distribution throughout the boiling range, hydrocarbon type as indicated by specific gravity, and acid heat, and tetraethyl lead content. It is our opinion, however, that although more elaborate correlations, involving more than laboratory octane numbers may be drawn, the refiner must still rely to a great extent, in cases of major importance, on actual road test results.

Volatility

The other major variable subject to refinery control is dependent upon the performance factors associated with proper fuel volatility. The tests most commonly used in specifying this phase of gasoline quality are Reid Vapor Pressure[4] and A.S.T.M. Distillation[5]. The Reid Vapor Pressure is a measure of the initial tendency of the fuel to vaporize, whereas the distillation test is a measure of the fractions of various boiling ranges that compose the gasoline.

Vapor lock, which is evidenced by fuel starvation due to vapor formation

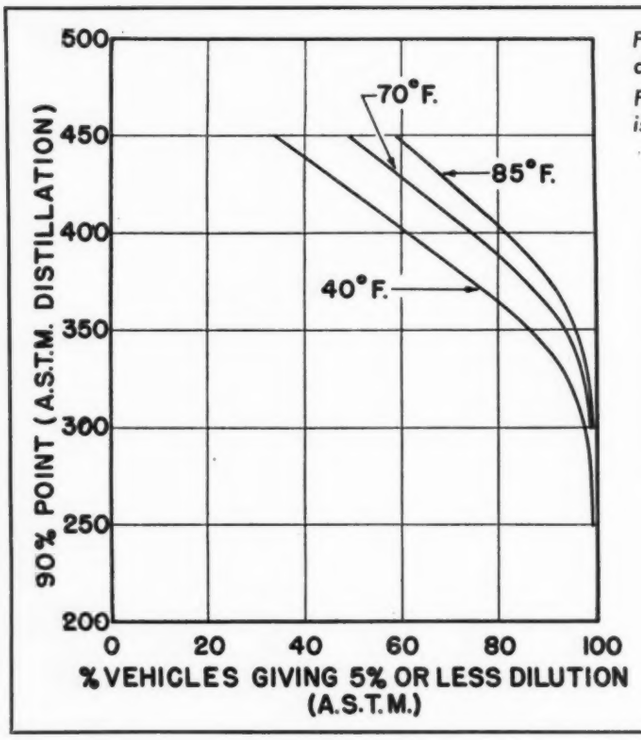
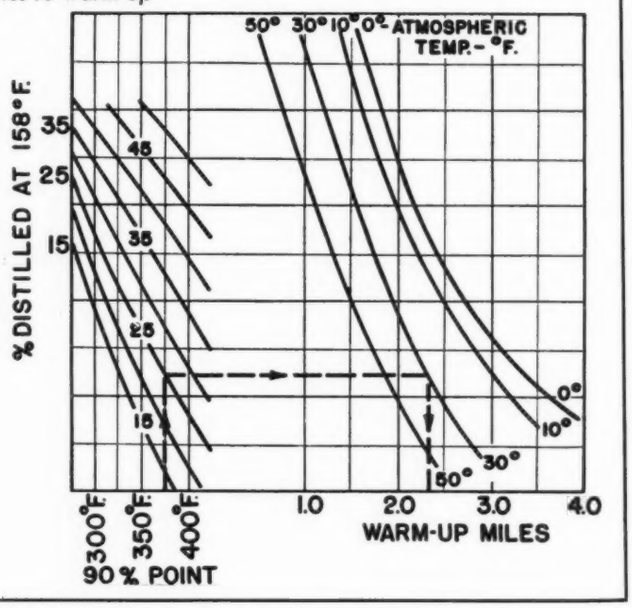


Fig. 3 (Left). Comparison of gasoline 90 percent and A.S.T.M. dilution. Note: All types of service included

Fig. 4 (Below). Relation of A.S.T.M. distillation characteristics to warm-up



in the fuel system or carburetor, can be related directly to vapor pressure. Road tests have proved this to be true for nearly all cars regardless of the hydrocarbon components giving rise to the vapor pressure; i.e., whether the vapor pressure is caused by propane, butane, or pentane alone or a combination of these hydrocarbons makes little apparent difference. The selection of vapor pressure as the criterion of vapor lock has been well established by extensive work in various laboratories over a number of years.[6] Fig. 2 presents a summary of this work, the data being presented on the same basis as in the case of anti-knock, so that the percentage of cars giving vapor lock under given atmospheric conditions with any specified vapor pressure can be readily estimated. It will be noted that atmospheric temperature is the determining factor in cases of vapor lock, so that this difficulty is decidedly a summer problem. The percentage of cars satisfied must be considerably greater than in the case of anti-knock performance, because although knocking is, to a large extent merely an annoyance, with severe vapor lock the engine simply will not run.

Ease of starting, which was in the past generally attributed to the fuel, is nowadays more dependent on the factors of cranking speed, ignition maintenance, and crankcase oil viscosity. No difficulty will be experienced in cold weather starting with practically any commercial gasoline, as nearly all of these fuels are considerably more volatile than required for this purpose.

The effect of fuel volatility on acceleration time has also been found to be very slight within the range of commercial fuels produced at the present time. It has been observed, however, that the use of more volatile fuels, such as many of the premium grades, although having no appreciable effect on acceleration time, often results in improved engine smoothness, which is noticed by many drivers. It is believed that this effect is due in part to more uniform manifold distribution with the lighter fuels, and is thus linked to the problem of satisfactory warmup.

Dilution of the crankcase oil is caused by the entry into the crankcase of unburned gasoline. Although this occurs most severely in starting from cold, particularly if the engine is flooded in so doing, a certain amount of dilution is encountered under operating conditions. Other factors being equal, it has been found that dilution can be correlated reasonably well with the 90 percent distillation point of the gasoline, insofar as normal types of fuel are concerned. By applying this correlation to results from a large number of vehicles of different types, engaged in all types of service, Fig. 3 has been derived. It has been assumed that a maximum dilution of 5 percent would be within safe limits, and Fig. 3 shows the percentage of cars that would be within this value at various atmospheric temperatures with fuels of various 90 percent points.

Perhaps the most critical performance characteristic that is influenced by overall fuel volatility is engine warm-up. It has been found that any fuel giving rapid warm-up will also start readily and give good acceleration. The proper formulation of warm-up specifications is thus of paramount interest to the refiner.

Considerable data have been accumulated that indicate that warm-up is a function of intake manifold temperature and fuel volatility it was found that the manifold temperature for a given car and given driving conditions rises at very nearly the same

Fig. 5. Refinery processes for manufacturing gasoline

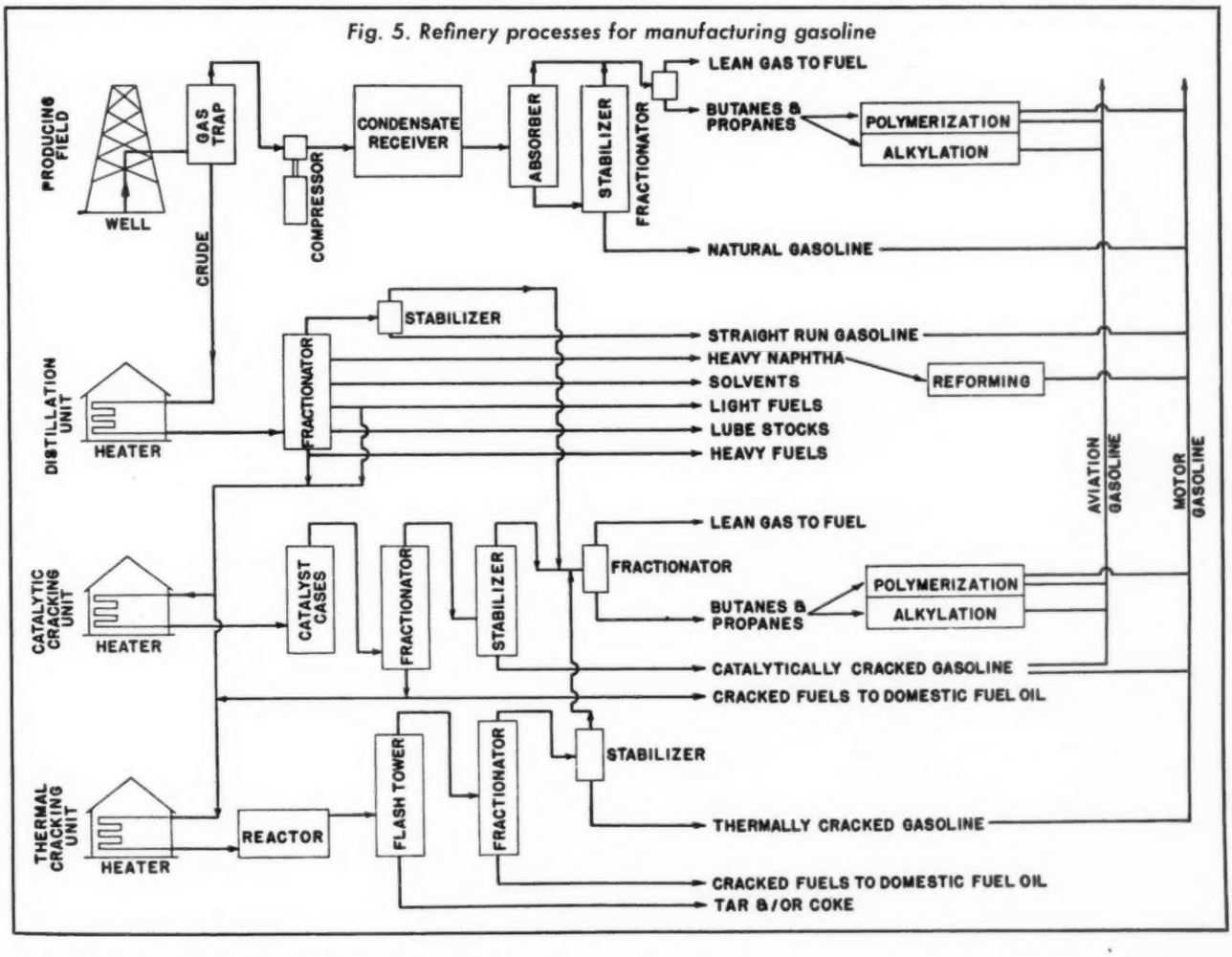
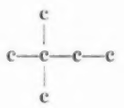


TABLE 1

Hydrocarbon series

Name	*Type formula*	*Structure*	*Typical members of series*
Paraffin	Cn H_{2n+2}	Straight chain	
*Iso*paraffin	Cn H_{2n+2}	Branched chain	
Olefin	Cn H_{2n}	Same as paraffins and *iso*paraffins except each molecule contains 2 less hydrogen atoms and therefore must have a double bond between 2 of the carbon atoms	
Naphthene	Cn H_{2n}	Ring	
Aromatic	Cn H_{2n-6}	6 carbon ring with 3 double bonds between carbon atoms	

rate, regardless of the fuel used. The temperature required before smooth acceleration is obtained varies among different fuels, however, depending on their vaporizing characteristics. These characteristics, it was found, could be controlled by specifying two points on the gasoline distillation curve.

For test purposes a rather severe procedure was adopted, which consisted of starting from cold and making successive accelerations at full throttle from 10 to 20 m.p.h. in high gear, with the minimum possible use of the choke. Warm-up was considered attained when accelerations were made smoothly without the use of the choke. Results were expressed in terms of "miles to warm-up." This technique follows the procedure used by other investigators[7] although the test conditions were purposely made more severe, so that "miles to warm-up" for comparable fuels are accordingly greater.

Results of this work were correlated with overall volatility expressed in terms of the percentage of fuel distilled at 158°F. and the temperature at which 90 percent was distilled, for several atmospheric temperatures, the warm-up time being naturally affected by the initial manifold temperature. This correlation is shown in Fig. 4.

Because of the variables involved, the use of Fig. 4 is somewhat complex, hence some explanation is in order. To find the relative warm-up performance of a fuel, start with the 90 percent point in the lower left corner, proceed upwards to the percent recovered at 158°F., across to the atmospheric temperature selected and downward to the scale of warm-up miles. The rate of manifold warm-up varies somewhat among car models, and the results shown on Fig. 4 represent a weighted average based on the percentage of makes on the road.

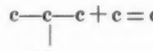
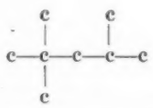
Field experience indicates that the average motorist would consider as excellent a fuel that gives warm-up in less than about 2 miles by this correlation. If, on the other hand, the warm-up is much over 4 miles, it is probable that under normal conditions the manifold would never reach a high enough temperature to provide smooth acceleration from 10 m.p.h. in high gear.

Having once established the warm-up miles desired in the fuel to be marketed in a given area, if the 90 percent point is fixed, it is possible to select the percentage that should be distilled at 158°F. The 90 percent point can be fixed from crankcase dilution considerations, previously discussed. In some cases federal, state or municipal specifications will fix this point. It is believed that the practice of a fixed 90 percent point to be maintained even during warm weather is to be discouraged. From the point of view of best economy consistent with satisfactory performance the 90 percent point should be varied from summer to winter as are the vapor pressure and other distillation characteristics.

Thus it is seen that although there is a considerable variety of desirable performance characteristics, they are not all subject to refinery control. Certain characteristics have been standardized through years of experience and are not subject to variation by reliable refiners. Others, although important to the customer, cannot be influenced to any great extent even by an extreme variation in fuel formulation. Although there may be more elaborate and accurate correlations, for practical purposes, the control of Research and Motor Method octane numbers, Reid Vapor Pressure, and A.S.T.M. Distillation constitute the main considerations in the art of gasoline manufacture.

TABLE 2

Type reactions in refining processes

Process	*Charge*	*Product*
Cracking	High molecular weight hydrocarbon such as gas oil or residuum	Gasoline range hydrocarbons and gas
	$C_{20}H_{42} \longrightarrow C_{10}H_{22}+C_{10}H_{20}$	
	or	
	$C_{20}H_{42} \longrightarrow C_{10}H_{20}+C_9H_{18}+CH_4$	
Reforming	High molecular weight hydrocarbons 300°F. to 450°F. boiling pt. such as heavy naphtha	Gasoline range hydrocarbons and gas
	Same type reactions as in cracking	
Polymerization	Gaseous olefins such as butylene	Gasoline range hydrocarbons
	$2C_4H_8 \longrightarrow C_8H_{16}$	
Alkylation	Gaseous *iso*paraffins and olefins *iso*butane and butylene	Gasoline range *iso*paraffins *iso*octane
		

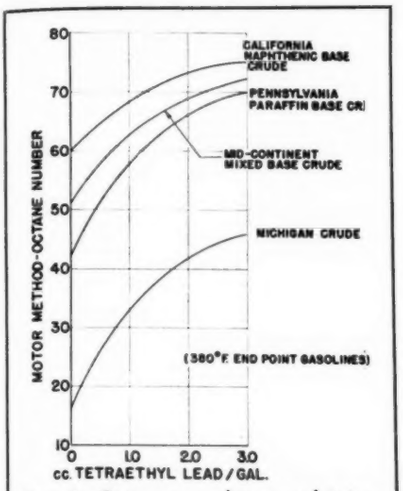


Fig. 6. Octane numbers and tetraethyl lead susceptibilities—straight run gasolines. Note: Research and motor method octane numbers of straight run gasolines—generally nearly equal

Petroleum Technology

In the early part of the century, the only means of producing gasoline was by simple distillation to recover the gasoline naturally occurring in crude oil. Today motor fuels are manufactured from both the higher and the lower boiling fractions of petroleum by the use of conversion processes. It has been estimated that a 90 percent yield of gasoline could be obtained from petroleum by using present commercial processes should the occasion demand.

To produce gasoline the manufacturer must select hydrocarbons of the proper distillation range from the crude oil, reduce the higher boiling fractions to a similar distillation range, and rearrange the molecular structure of individual hydrocarbons to the extent that such rearrangement is economical. In addition, the undesirable impurities present in the raw products must be rejected, and usually oxidation inhibitors must be added to improve stability and reduce gum-forming tendencies. Tetraethyl lead is almost always added to gasoline to improve its octane rating. As technical knowledge on many of the operations involved is incomplete, petroleum refining is not an exact science and results are largely comparative.

A fairly good picture of the methods in use today for the manufacture of gasoline is given in the attached flow chart, Fig. 5. It should be pointed out that the arrangement shown is not necessarily the same as would be used in any given refinery but rather points out the various processing possibilities. The more important refinery processes are briefly described in the following pages.

It will be realized that the chemistry of hydrocarbon technology is extremely complex. Although any exposition of the subject is far beyond the scope of this paper, an attempt has been made to present, in Tables 1 and 2, a few elementary definitions and diagrams that it is hoped will help clarify the discussion of the various refinery processes.

Control of Volatility

In general, volatility control is obtained in distillation and stabilization equipment following various processing operations. Refinery conversion processes, with one or two exceptions noted later, are controlled primarily toward producing gasoline with the highest anti-knock quality conducive to economical yield.

Vapor pressure is controlled in stabilizer equipment by varying the content of the highest vapor-pressure components in the gasoline. These are, obviously, the lowest boiling fractions and consist almost entirely of hydrocarbons of four carbon atoms. The average vapor pressure of this mixture of butanes and butenes is about 60 lb. per sq. in. and the amount of this material present in gasoline is varied from about 8 percent in summer to about 12 percent in winter. In the winter the refiner is usually able to use most of the butanes and butenes that are available to him in crude oil and from conversion processes, but under summer conditions in most localities it is often impossible to recover more than 50 percent in motor fuel. The remainder must be used at lower returns as boiler and furnace fuel unless conversion equipment is at hand to process it to gasoline.

Overall fuel volatility is controlled in fractionating equipment both by varying the amount of light fractions available and by adjusting the final boiling point of products from the various refinery operations. In general, light fractions additional to those produced in ordinary crude topping and cracking operations are obtained by processing heavy gasoline fractions, purchasing natural gasoline of high volatility, and operation of gas recovery equipment up to the maximum butane allowable by the vapor-pressure specifications. For flexibility in volatility control, the refiner must rely to a large extent on varying the endpoint of the products from the various operations. The technique in endpoint control consists in cutting the various stocks to different endpoints, depending on the octane number of the base stocks. It will be noted in the following paragraphs that the straight run stocks fall off very rapidly in octane number whereas catalytically cracked stocks show very little change in octane number as the endpoint is increased, and that thermally cracked stocks are intermediate in this respect. Therefore it is good practice to cut very low endpoints on straight run distillates and go to higher endpoints in the various cracked stocks.

The heavy straight run fractions may be converted to lighter material of higher anti-knock value by reforming or cracking, as discussed in subsequent paragraphs.

Control of Anti-knock Quality

The refiner's controls over anti-knock quality of motor fuels are:

1. Selection of crude oil.
2. Choice of refining process.
3. Regulation of the addition of tertraethyl lead.

All three of these possible choices are very closely interrelated and cannot be considered individually as brought out in the following discussion.

Tetraethyl lead is added to most gasolines sold in the United States to improve the anti-knock qualities. Other anti-knock additives are known, but they are not widely used, mainly because of economic disadvantages.

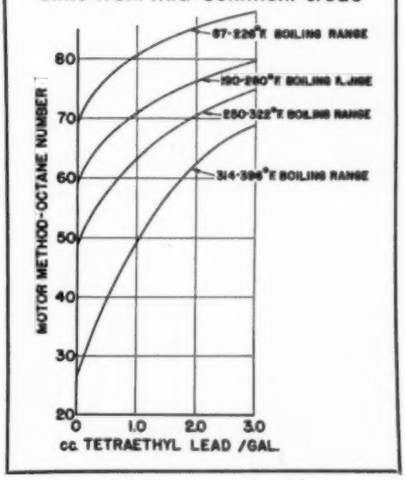
The improvement in anti-knock quality obtained with ethyl fluid varies considerably with the type of gasoline, and the economic success of a refining process may depend to a large extent upon the response of the product to tetraethyl lead. It will be pointed out in the following descriptions of conversion processes, which are available to the refiner, the effectiveness of tetraethyl lead upon motor fuels obtained from those processes.

Straight Run Gasoline

About 260,000,000 bbl. of gasoline per year are produced in the United States by simple distillation of crude

(Continued on Page 258)

Fig. 7. Octane numbers and tetraethyl lead susceptibilities. Narrow boiling fractions—straight run gasoline from Mid-Continent crude



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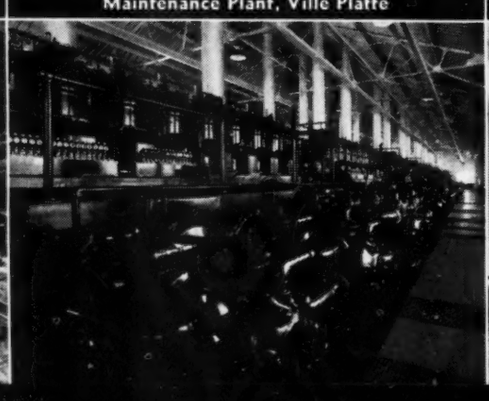
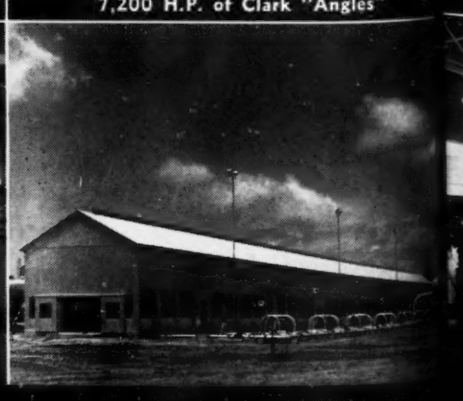
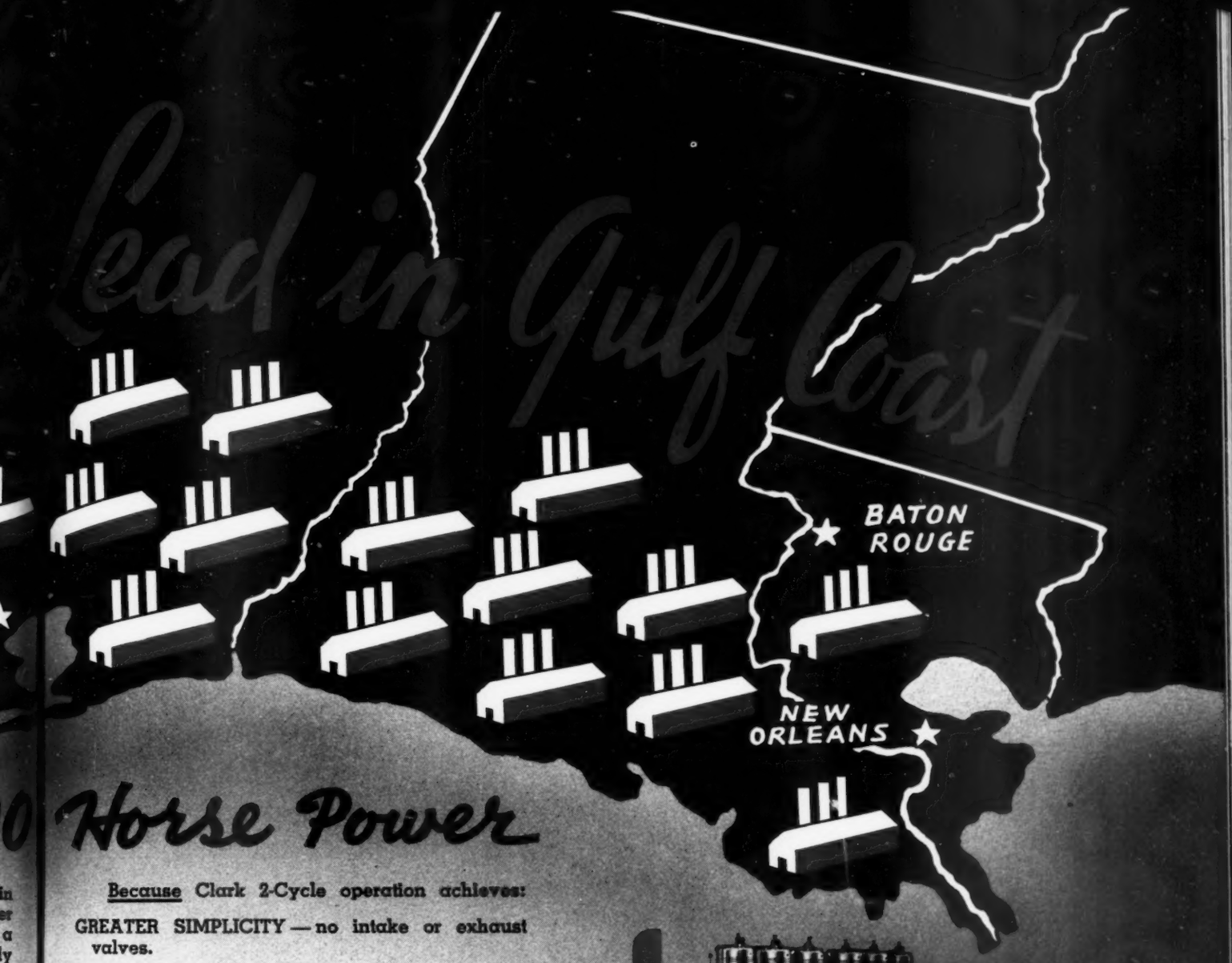
La Gloria Condensate Recovery Plant, Texas Gulf Coast

8,600 H.P. of Clarks, Pressure Maintenance Plant, Ville Platte



Cotton Valley Recycling Plant, 7,200 H.P. of Clark "Angles"





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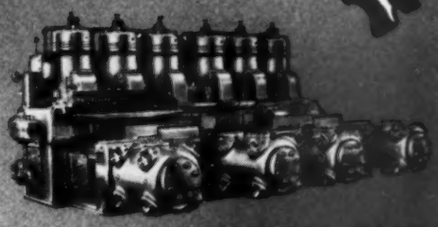
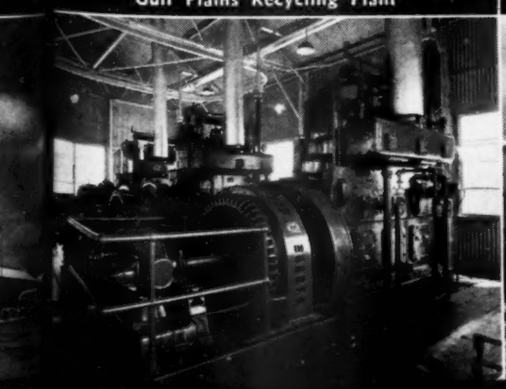


CLARK 6 Cyl., 600 H.P. "Angle" Compressor

AFFILIATED COMPANIES:
Dresser Mfg. Co., Bradford, Pa.; Pacific Pump Works, Huntington Park, Calif.; Bryant Heater Company, Cleveland, Ohio.

LARK

Clark "Angles" Driving Generators, Gulf Plains Recycling Plant



View, World's Largest Pressure Maintenance Plant, Ville Platte, La.

8,800 H.P. of Clark 8-cylinder "Angles", La Gloria Plant

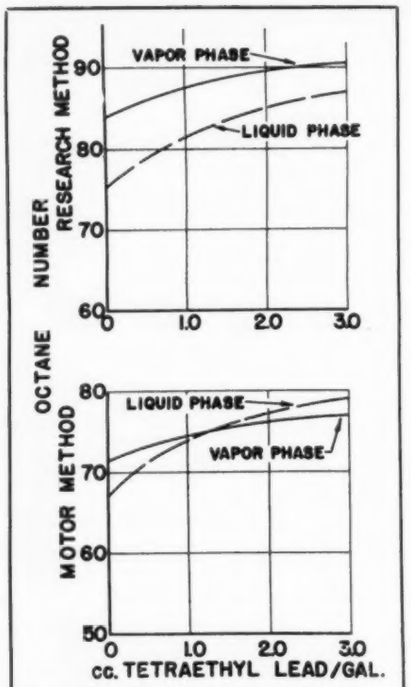


Fig. 8. Octane numbers and tetraethyl lead susceptibilities—thermally cracked gasolines. (400°F.E.P.—from Mid-Continent gas oil)

(Continued from Page 255)

oil. The yield obtained in any particular case varies widely, with the crude, as some crude oils contain almost no gasoline and others contain very little else. An average gasoline yield would be about 25 percent. The anti-knock quality will also vary widely depending on the type of crude processed. Fig. 6 shows the octane number and lead susceptibility curves of four typical stocks with a 380°F. endpoint.

Another significant anti-knock quality characteristic of straight run gasolines is the fact that in most cases octane number decreases substantially with increasing endpoint. Fig. 7 shows this effect in a gasoline distilled from a Mid-Continent crude. General refinery procedure is to use in final blending straight run gasolines with endpoints below 300°F. The fraction boiling in a range next above this, generally 300°F. to 450°F. or higher, is reformed to increase its octane number and volatility.

Research and Motor Method octane numbers of straight-run fuels are not far apart, and therefore these fuels do not show any reduction in road anti-knock quality at high speeds.

Thermal Cracking

The most common process for converting high boiling petroleum constituents into gasoline is thermal cracking. This process is responsible for the production of about half of the 600,000,000 bbl. of gasoline produced in the United States annually.

Thermal cracking involves breaking down long chain hydrocarbons above the gasoline boiling range into smaller molecules within the gasoline boiling range. The formation of non-condensible gases, heavy industrial fuel oils, and coke occurs simultaneously. This conversion may be carried out under a wide range of high temperatures and at various pressures. These cracking conditions are dictated largely by the type of stock to be processed and by the gasoline yield and quality desired, giving due consideration to factors affecting economics, such as gas formation, coke formation, and cracking unit maintenance. Higher temperatures and lower pressures are used in "vapor" phase cracking than are used in "liquid" phase cracking. The former is generally accompanied by higher gas losses and results in a more volatile gasoline of higher anti-knock quality.

As indicated above, the type of charging stock greatly influences cracking conditions and characteristics of the gasoline product. Cracking stocks may vary with respect to boiling range and hydrocarbon composition. In general, charging stocks in the higher boiling ranges are more easily cracked than those in the lower boiling ranges and therefore, do not need to be subjected to as high temperature conditions. Likewise, paraffinic charging stocks break down more readily than aromatic and naphthenic materials.

Gasoline yields may vary widely with cracking stocks and cracking conditions, averaging about 50 percent.

Cracked gasolines contain a considerable proportion of olefines, which contribute particularly to their high anti-knock quality. These materials, however, tend to absorb oxygen and join to one another during storage to form high boiling constituents that would not vaporize in the carburetting and manifold system of the engine resulting in gummy deposits in the manifold and on intake valves. During recent years it has been found that this gum-forming tendency can be eliminated for storage periods of a year or more by the addition of oxidation inhibitors. As little as one part anti-oxidant in 300,000 parts of gasoline is all that is necessary. Problems arising from gum in gasoline are now practically non-existant in automotive applications.

Fig. 8 shows the octane numbers and tetraethyl lead susceptibilities of two typical thermally cracked gasolines. It will be noted that the vapor-phase cracked product has a higher initial octane number, but a poorer tetraethyl lead susceptibility. This is an attribute of the high olefinic hydrocarbon content of that product. Unlike straight-run gasolines, wide spreads between Research and Motor Method octane numbers exist, increasing with the severity of the cracking treatment. This characteristic, again due largely to olefinic and also aromatic hydrocarbons, is responsible for the so-called knock "sensitivity" at high speeds the tendency for such fuels to show a decrease in road anti-knock quality at high speeds. Further, as shown in Fig. 9, the spread in anti-knock quality between light and heavy fractions of cracked gasolines, is less than in the case of straight run stocks.

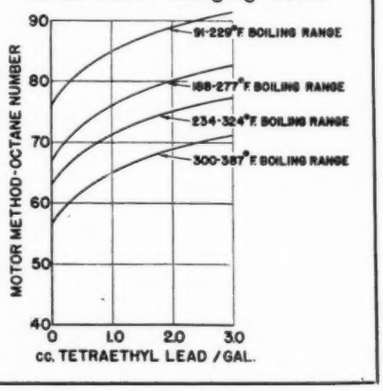
Catalytic Cracking

About 30,000,000 bbl. of cracked gasoline are produced by the catalytic process each year, and the use of this type of operation is being extended rapidly.

As in thermal cracking long chain hydrocarbons above the gasoline boiling range are broken down into smaller molecules that boil within the gasoline range. However, this cracking takes place in the presence of a catalyst that serves not only to facilitate the ruptured hydrocarbon chains, but also controls the mechanism of their destruction along certain paths to form less olefinic materials and more materials of the branched chain and aromatic types, which display better anti-knock characteristics than olefins. Non-condensible gases and products of the domestic fuel oil variety, generally called gas-oils have formed simultaneously. The latter make excellent charging stocks to thermal cracking units resulting in gasolines somewhat higher in anti-knock quality than those produced from virgin gas-oils.

Catalytic cracking may be carried out from 800 to 950°F. Unlike thermal

Fig. 9. Octane numbers and tetraethyl lead susceptibilities. Narrow boiling fractions — thermally cracked gasoline. (Liquid phase E. Texas resid. charging stock)



cracking, low pressures usually less than 10 lb. per sq. in. are used.

In general, the yield of gasoline will be about 45 percent based on charge to the catalyst. The octane number (A.S.T.M.) of the gasoline produced from practically any charging stock is from 76 to 81. This is an outstanding characteristic of catalytic processing. Fig. 10 shows lead susceptibility curves of catalytically cracked gasolines from two different charging stocks. Response to lead is excellent considering the high initial octane number. Spread between Research and Motor Method rating is large, due principally to aromatic hydrocarbon content.

Fig. 11 indicates that the octane number does not change to any great extent with boiling range.

Reforming

Reforming is the term applied to the cracking of stocks in the gasoline boiling range or slightly above it. The hydrocarbon chains are rearranged under temperatures in excess of 1000°F. and high pressures in the thermal process or under milder conditions catalytically to raise the octane number and at the same time to obtain a gasoline stock with a lower boiling range, more suitable for inclusion in the finished motor fuel. As in the case of cracking, catalytic reforming gives products superior to those obtained from the thermal process. Hydro-forming is the term applied to a catalytic process for reforming in the presence of hydrogen.

Yields of gasoline usually range from 80 to 90 percent depending upon the severity of processing conditions. Some light gases and a small quantity of fuel oil account for the remainder of the charge. In quality, reformed gasoline is much like the cracked gasoline produced from heavier portions of the same crude. Fig. 12 shows lead susceptibilities and Motor and Research octane numbers of a thermally reformed gasoline.

Polymerization

The processes of thermal and catalytic cracking produce annually about 300,000,000,000 cu. ft. of gas. This gas was formerly either burned as refinery fuel or wasted, but much of it is now converted to gasoline by polymerization processes[9]. The gasoline produced in this way amounts to about 3 percent of the total gasoline made in the United States.

Polymerization is the reverse of cracking. In other words, it is the linking of two or more molecules to form one molecule having a longer carbon chain and a higher boiling point. The importance of such an operation as a conservation measure is obvious. In addition, the gasoline formed is generally very high in anti-knock quality.

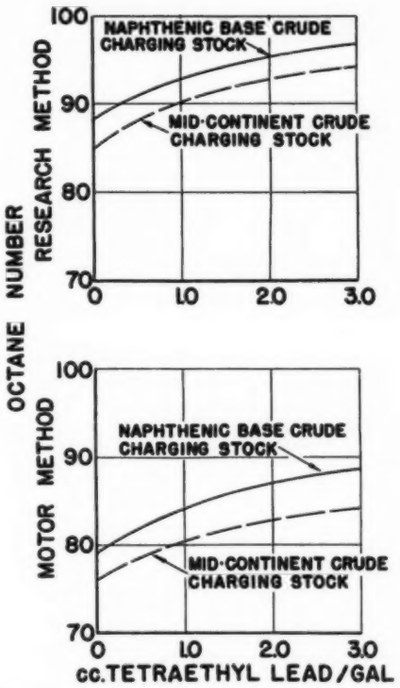


Fig. 10. Octane numbers and tetraethyl lead susceptibilities—catalytically cracked gasolines

Polymerization can be effected either thermally or with the aid of a catalyst. In the thermal process, both olefines and paraffins can be utilized, the paraffins probably being dehydrogenerated under the high temperature conditions (about 1200°F.) before linking with the other olefins present. The primary products of polymerization are olefins, but various side reactions also take place, and the resulting gasoline contains aromatics, paraffins, and napthenes as well. Because of the high olefin content, the gasoline has a relatively low tetraethyl lead susceptibility and a marked tendency toward high-speed knock. Catalytically polymerized gasoline contains more olefins than does the thermal product, and has, therefore, a somewhat higher octane number and lower lead susceptability.

Octane numbers and lead susceptability data for thermal and catalytically polymer gasolines are shown in Fig. 12.

Polyforming

The term "polyforming" has been applied to a recently developed process wherein thermal polymerization of gases is combined with reforming[10]. The charge to this operation usually consists of the propane and butane fractions from the other refinery units, plus heavy straight run naphtha. The operation is carried out at from 1025° to 1125°F. and from 1000 to 2000 lb. per sq. in. pressure. Under these conditions cracking and polymerization proceed simultaneously along with various complex side reactions. The unreacted propane and butane is recycled so that a high yield of gasoline is obtained. The product is similar in quality to thermal polymer gasoline. A comparison of the octane numbers and lead susceptibilities of these gasolines is shown in Fig. 12.

Alkylation

Alkylation is the term applied to the reaction of an olefin with a paraffin or saturated hydrocarbon. The products consist almost entirely of members of the *iso*paraffin hydrocarbon series in the gasoline boiling range. These materials have a highly branched molecular structure and are very high both in anti-knock quality and in susceptibility, to tetraethyl lead. In addition they are much more stable than the gasolines produced by cracking or polymerization. This process is used to produce *iso*octane from *iso*butane and butylene. Neo-hexane, another fuel of very high anti-knock quality, is produced by reacting ethylene and *iso*butane.

Alkylation to produce commercial *iso*octane is carried out under very low temperatures and pressures using sulphuric acid as a catalyst[11]. Neo-hexane is manufactured at present by a thermal process using temperatures of 1200°F. and pressures above 3000 lb. per sq. in[12]. At the present time, both products are used exclusively for the manufacture of aviation gasoline of high anti-knock quality. One hundred octane number aviation gasoline usually contains from 40 percent to 50 percent of either of these blending agents. Present alkylate and *iso*octane production amounts to about 1 percent of total gasoline made in the United States[13].

Future Trends

The present war will accelerate new developments and make available fuel types that would normally require years to produce. For the duration the use of such fuels will be confined largely to military operations. The immediate effect on fuels for civilian use will be to force endpoints higher and octane numbers lower in an effort to increase gasoline yield and decrease tetraethyl lead consumption. Demands by the armored forces as well as by military aviation will result in diversion of the highest octane number stocks now available to these users.

Research activities are now stimulated by the demand for fuels of higher quality to give greater power, flexibility, and operating range to military equipment. The eventual result will

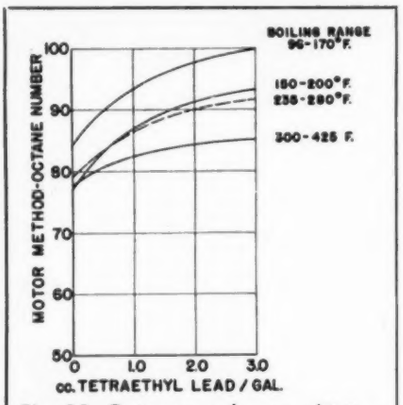


Fig. 11. Octane numbers and tetraethyl lead susceptibilities—narrow boiling fractions, catalytically cracked gasoline

probably be the formulation, at a price, of an ultimate gasoline. Even now, such a fuel is theoretically possible from purely scientific considerations. As the art of synthesizing hydrocarbon molecules advances, a gasoline could be made consisting of a blend of pure hydrocarbons, each contributing its own particular characteristics. The result would be a composite fuel of suitable volatility, high power output and low fuel consumption for all super-power demands. Some blending agents of very high quality are already available in reasonably large quantities for aviation gasoline production. Commercial *iso*-octane, neo-hexane, and *iso*pentane fall into this category. Certain other compounds, notably aromatics, demonstrate important advantages when burned under rich mixture conditions as used for take-off and fighting operations with highly supercharged aviation engines.

It is beyond question that further changes in automotive engine design will be accelerated by wartime activity, and that at least some of the features of aero engine design will find application in automotive uses. Many of these changes will be for the purpose of obtaining better performance and economy from better grade fuels. It is the belief of some engineers that supercharging is the most obvious step in this direction, as the gains from further compression ratio increases appear to be limited. It would appear of equal importance to develop engine changes to take better advantage of the characteristics of current motor fuels, along the lines of better manifolding, better mixture control and better spark advance control.

Although in the future special fuels will be available for purposes where high outputs are essential and cost is not a primary consideration, it is likely that for some time to come the most economical power plant combination will require an engine capable of using to the best advantage fuels of present-day quality.

Conclusions

It has been pointed out that of the many gasoline characteristics in which the consumer is interested, a limited number are subject to close control by the refiner. The most important of these are anti-knock quality, vapor pressure, and distillation. The various processes that the refiner uses to control the properties of gasoline involve to a considerable extent the complete rebuilding of the crude oil molecules that form the starting point of the refining process. The refiners problem includes not only the manufacture of gasoline to meet a variety of automotive requirements, but the production of sufficient quantities of fuel with the greatest economic efficiency.

The art of petroleum refining is more and more dependent on the technologist in performing this task. The ultimate in quality appears in the form of hydrocarbon molecules of highly effective characteristics. The most economical utilization of our crude oil resources consistent with the cost of the automotive equipment using the fuel will probably never call for the formulation of such gasolines except for very special purposes. It is hoped that the automotive designer will benefit from a consideration of the type of information offered herein. It is also hoped that he will be encouraged to work even more closely with the refiner and the petroleum technologist in solving their mutual problem of providing cheap power.

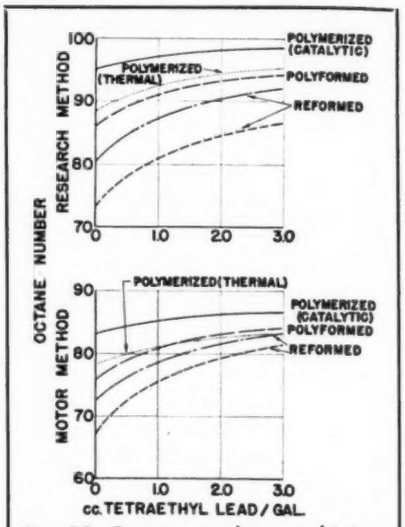


Fig. 12. Octane numbers and tetraethyl lead susceptibilities—polymerized, reformed, and polyformed gasolines

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SINCE 1890

Thermodynamic Properties of Propane*

By WALTER V. STEARNS‡ and EMMANUEL J. GEORGE
Sun Oil Company

THE use of propane as a refrigerant has increased substantially within the last few years, and thermodynamic data for this refrigerant have not been compiled for the whole region normally employed in refrigeration. Although Dana et al.[2] published tables for the saturated liquid and vapor, no satisfactory compilation has been made for the superheated vapor region.

This paper represents a close correlation of the published experimental data of a number of authors on certain phases of the thermodynamic properties of propane. Although Sage, Schaafsma, and Lacey[10] and Burgoyne[1] published thermodynamic charts, the data used in calculating these charts did not show the agreement between the experimental data pointed out in this paper. By correlating the actual experimental data of the authors cited, we have been able to show close agreement between the results of these authors. This agreement may be best understood if the following processes are examined. If, for example, we take the saturated liquid at —40°F., evaporate this liquid to the saturated vapor, heat the resulting vapor at constant pressure to 160°F., and compress it isothermally until the saturated vapor is reached, the actual heat content of the resulting vapor will then agree within about 0.2 B.t.u. with the heat content of the vapor that would be obtained by heating the saturated liquid to 160°F. and then evaporating the liquid to form a saturated vapor. Such agreement is possible only if all these various thermodynamic factors are correct or if two or more of these factors will produce compensating errors over the complete range. The latter probability is somewhat remote, in view of the complexity of the functions involved. This paper presents the first correlation of the thermodynamic properties of propane based on purely experimental data and although these experimental data are not so complete as would be desired, the overall picture is in close agreement.

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‡Now with M. W. Kellogg Company.

Properties Investigated

The vapor pressure values employed in these correlations are calculated from the formula:

$$\log P = A/T + B \log T + C$$

Where:

$A = -1018.502$
$B = -0.16646$
$C = +6.67979$
P = absolute pressure, cm. Hg
T = absolute temperature, °K.

These values agree well with those of Kemp and Egan[6] above —80°F., with the low-temperature values of Dana et al., and with the values of Deschner and Brown[3] to about +195°F. From +195°F. up to and including the critical point, the values of Deschner and Brown are utilized. For temperatures below —43.7°F. the specific heats of the liquid of Kemp and Egan[6] are employed. From —43.7° to +155°F., the values represent a smooth curve through the data of Dana et al. and of Sage and Lacey. The values of Sage and Lacey[9] are apparently a revision of the earlier data of Sage, Schaafsma, and Lacey.[10] Above +155°F. the values are drawn as a smooth curve roughly following the values of Sage, Schaafsma, and Lacey at the lower end and to the observed values of these authors at the higher end corrected for their deviation from the apparent true critical temperature.

The heats of fusion are taken from the observations of Kemp and Egan.

The values for latent heat were taken from a smooth curve drawn through the experimental values of Kemp and Egan,[6] Dana et al.,[2] and of Sage, Evans, and Lacey.[8]

The specific volume and density of the liquid are taken from a smooth curve through the values of Dana,[2] Sage, Schaafsma, and Lacey,[10] and Deschner and Brown.[3] The data for the compressed liquid are taken from Deschner and Brown.

The specific volumes of the saturated vapor show good agreement between the experimental values of Dana et al. and of Deschner and Brown. The tabulated calculated data of Dana are not in agreement and showing increasing divergence with increasing temperature.

Specific volumes of superheated vapor were calculated from compressibility factors as based on Deschner and Brown.

These values were plotted and extrapolated on a large-scale chart. A few

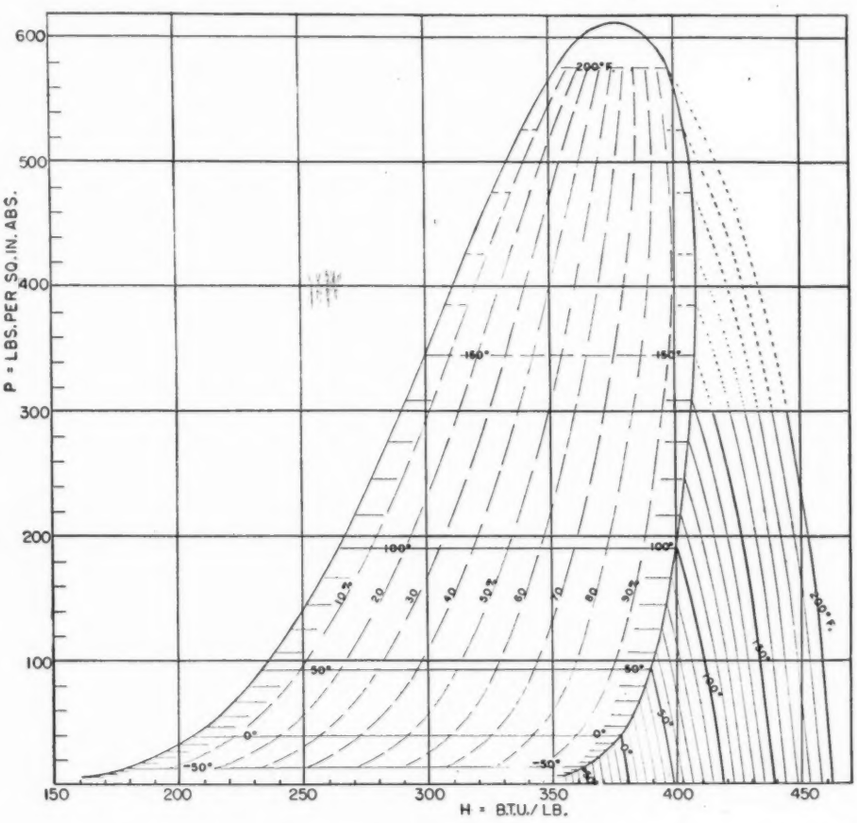

Fig. 1. Absolute enthalpy chart for propane

TABLE I

Temperature data for saturated propane

Temperature t, ° F.	Pressure, Lb./Sq. In. Absolute, P	Pressure, Lb./Sq. In. Gage, gp	Volume, Cu. Ft./Lb. Liquid v	Volume, Cu. Ft./Lb. Vapor V	Density Liquid $(1/v)$, lb./gal.	Density Vapor $(1/V)$, lb./cu. ft.	Heat Content, B. T. U./Lb. Liquid h	Heat Content, B. T. U./Lb. Vapor H	Latent Heat L, B. T. U./Lb.	Entropy, B. T. U./Lb./° F. Liquid s	Entropy, B. T. U./Lb./° F. Vapor S
−80	5.65		0.0265	16.2	5.052	0.062	162.6	354.0	191.4	0.8794	1.3832
−78.75	5.87	18 in.[a]	0.0265	15.6	5.043	0.064	163.2	354.4	191.2	0.8812	1.3826
−78	6.00		0.0266	15.3	5.041	0.065	163.6	354.6	191.0	0.8821	1.3822
−76	6.32		0.0266	14.6	5.030	0.068	164.6	355.2	190.6	0.8847	1.3812
−75.9	6.35	17 in.	0.0266	14.6	5.030	0.068	164.6	355.2	190.6	0.8850	1.3811
−74	6.71		0.0267	13.8	5.020	0.072	165.6	355.8	190.2	0.8874	1.3801
−73.2	6.86	16 in.	0.0267	13.5	5.019	0.074	166.0	356.0	190.0	0.8884	1.3797
−72	7.18		0.0268	13.0	5.009	0.076	166.6	356.4	189.8	0.8900	1.3791
−70.7	7.35	15 in.	0.0268	12.7	5.002	0.079	167.2	356.5	189.5	0.8918	1.3785
−70	7.48		0.0268	12.5	4.998	0.080	167.6	357.0	189.4	0.8927	1.3781
−68.4	7.84	14 in.	0.0268	12.0	4.990	0.083	168.4	357.5	189.1	0.8949	1.3775
−68	7.91		0.0268	11.9	4.988	0.084	168.6	357.6	189.0	0.8954	1.3773
−66.1	8.32	13 in.	0.0268	11.3	4.978	0.088	169.8	358.1	188.5	0.8978	1.3766
−66	8.33		0.0269	11.3	4.978	0.088	169.7	358.2	188.5	0.8980	1.3765
−64	8.80		0.0269	10.8	4.968	0.093	170.7	358.8	188.1	0.9007	1.3756
−63.9	8.81	12 in.	0.0269	10.8	4.968	0.093	170.8	358.9	188.1	0.9008	1.3756
−62	9.28		0.0270	10.3	4.957	0.097	171.7	359.4	187.7	0.9033	1.3748
−61.9	9.30	11 in.	0.0270	10.3	4.957	0.097	171.8	359.5	187.7	0.9034	1.3748
−60	9.78	10 in.	0.02703	9.77	4.946	0.102	172.7	360.0	187.3	0.9060	1.3740
−58.1	10.28	9 in.	0.02709	9.35	4.936	0.107	173.6	360.5	186.9	0.9085	1.3732
−58	10.29		0.02709	9.33	4.936	0.107	173.7	360.6	186.9	0.9086	1.3732
−56.2	10.77	8 in.	0.02714	8.96	4.926	0.112	174.6	361.1	186.5	0.9108	1.3726
−56	10.80		0.02715	8.92	4.925	0.112	174.7	361.1	186.4	0.9111	1.3725
−54.4	11.26	7 in.	0.02720	8.59	4.917	0.116	175.6	361.4	185.8	0.9132	1.3719
−54	11.36		0.02721	8.51	4.915	0.117	175.8	361.7	185.9	0.9137	1.3717
−52.6	11.75	6 in.	0.02725	8.24	4.907	0.120	176.5	362.1	185.6	0.9154	1.3712
−52	11.95		0.02727	8.12	4.904	0.122	176.8	362.3	185.5	0.9162	1.3710
−51	12.24	5 in.	0.02730	7.93	4.898	0.125	177.3	362.6	185.3	0.9175	1.3706
−50	12.60		0.02733	7.73	4.893	0.129	177.8	362.8	185.0	0.9188	1.3702
−49.6	12.73	4 in.	0.02734	7.72	4.891	0.130	178.0	362.9	184.9	0.9193	1.3701
−48	13.20		0.02739	7.50	4.882	0.133	178.8	363.4	184.6	0.9213	1.3696
−47.9	13.22	3 in.	0.02739	7.44	4.883	0.134	178.9	363.5	184.6	0.9214	1.3696
−46.5	13.71	2 in.	0.02743	7.17	4.875	0.139	179.7	363.8	184.1	0.9232	1.3691
−46	13.85		0.02745	7.06	4.872	0.142	179.9	364.0	184.1	0.9238	1.3689
−44.9	14.2	1 in.	0.02748	6.90	4.866	0.145	180.4	364.3	183.9	0.9252	1.3686
−44	14.52		0.02751	6.74	4.861	0.148	180.9	364.6	183.8	0.9264	1.3683
−43.71	14.70	0	0.02752	6.66	4.860	0.150	181.36	364.76	183.5	0.9266	1.3682
−42	15.28		0.02757	6.42	4.850	0.156	181.9	365.2	183.3	0.9289	1.3676
−40	16.00	1.30	0.02763	6.16	4.839	0.162	183.0	365.7	182.7	0.9315	1.3670
−38	16.79	2.09	0.02769	5.92	4.828	0.169	184.0	366.3	182.3	0.9340	1.3664
−36	17.56	2.86	0.02775	5.66	4.818	0.177	185.1	366.9	181.8	0.9365	1.3658
−34	18.40	3.70	0.02782	5.44	4.807	0.184	186.2	367.5	181.3	0.9391	1.3652
−32	19.30	4.60	0.02788	5.22	4.797	0.192	187.3	368.0	180.7	0.9416	1.3646
−30	20.18	5.48	0.02794	5.02	4.786	0.199	188.4	368.6	180.2	0.9441	1.3640
−28	21.05	6.35	0.02800	4.82	4.775	0.207	189.4	369.2	179.7	0.9467	1.3634
−26	22.01	7.31	0.02807	4.63	4.764	0.216	190.5	369.8	179.3	0.9492	1.3628
−24	22.98	8.28	0.02813	4.44	4.752	0.225	191.6	370.3	178.7	0.9517	1.3622
−22	23.98	9.28	0.02820	4.25	4.741	0.235	192.7	370.9	178.2	0.9543	1.3616
−20	25.05	10.35	0.02826	4.06	4.730	0.246	193.8	371.5	177.7	0.9568	1.3610
−18	26.15	11.45	0.02833	3.90	4.719	0.256	194.9	372.1	177.2	0.9592	1.3604
−16	27.30	12.60	0.02839	3.76	4.708	0.266	196.0	372.7	176.6	0.9617	1.3599
−14	28.50	13.80	0.02846	3.61	4.697	0.277	197.1	373.2	176.1	0.9641	1.3593
−12	29.70	15.00	0.02852	3.47	4.686	0.288	198.2	373.8	175.6	0.9666	1.3588
−10	30.95	16.25	0.02859	3.33	4.675	0.300	199.4	374.4	175.0	0.9690	1.3582
− 8	32.23	17.53	0.02866	3.20	4.664	0.313	200.5	375.0	174.5	0.9714	1.3577
− 6	33.55	18.85	0.02873	3.08	4.652	0.325	201.6	375.5	173.9	0.9739	1.3571
− 4	35.00	20.30	0.02879	2.98	4.641	0.336	202.7	376.1	173.4	0.9763	1.3566
− 2	36.40	21.70	0.02886	2.86	4.629	0.350	203.8	376.7	172.8	0.9788	1.3560
− 0	37.81	23.11	0.02893	2.74	4.618	0.365	205.0	377.2	172.2	0.9812	1.3555
+ 2	39.30	24.60	0.02900	2.66	4.607	0.376	206.1	377.8	171.6	0.9836	1.3550
4	40.85	26.15	0.02908	2.56	4.596	0.391	207.2	378.3	171.1	0.9860	1.3545
6	42.50	27.80	0.02915	2.47	4.584	0.405	208.4	378.9	170.5	0.9884	1.3541
8	44.13	29.43	0.02923	2.38	4.573	0.420	209.6	379.5	169.9	0.9908	1.3536
10	45.85	31.15	0.02930	2.30	4.562	0.435	210.7	380.0	169.3	0.9932	1.3531
12	47.55	32.85	0.02938	2.22	4.550	0.450	211.9	380.6	168.7	0.9956	1.3527
14	49.35	34.65	0.02946	2.14	4.538	0.467	213.1	381.1	168.0	0.9979	1.3523
16	51.20	36.50	0.02954	2.08	4.526	0.481	214.2	381.6	167.4	1.0003	1.3518
18	53.10	38.40	0.02962	2.00	4.514	0.500	215.4	382.1	166.7	1.0026	1.3514
20	55.00	40.30	0.02970	1.93	4.502	0.518	216.6	382.6	166.0	1.0050	1.3510
22	57.05	42.35	0.02978	1.86	4.590	0.538	217.7	383.1	165.4	1.0073	1.3506
24	59.10	44.40	0.02986	1.79	4.477	0.559	218.8	383.6	164.8	1.0097	1.3502
26	61.25	46.55	0.02995	1.73	4.465	0.578	220.0	384.1	164.2	1.0120	1.3499
28	63.45	48.75	0.03003	1.67	4.452	0.598	221.2	384.6	163.5	1.0144	1.3495
30	65.70	51.00	0.03011	1.60	4.440	0.625	222.3	385.1	162.8	1.0167	1.3491
32	67.95	53.25	0.03020	1.54	4.427	0.649	223.4	385.6	162.2	1.0190	1.3487
34	70.33	55.63	0.03029	1.48	4.414	0.676	224.5	386.1	161.5	1.0213	1.3484
36	72.75	58.05	0.03037	1.43	4.401	0.699	225.6	386.6	160.8	1.0237	1.3480
38	75.20	60.50	0.03046	1.39	4.388	0.719	226.8	387.1	160.2	1.0260	1.3477
40	77.80	63.10	0.03055	1.33	4.375	0.752	227.9	387.5	159.6	1.0283	1.3473
42	80.40	65.70	0.03064	1.28	4.362	0.781	229.1	388.0	158.9	1.0306	1.3470
44	83.05	68.35	0.03073	1.25	4.348	0.800	230.2	388.5	158.2	1.0329	1.3466
46	85.83	71.13	0.03083	1.21	4.335	0.826	231.4	389.0	157.5	1.0352	1.3463
48	88.65	73.95	0.03092	1.17	4.321	0.855	232.6	389.5	156.8	1.0375	1.3459
50	91.50	76.80	0.03101	1.14	4.308	0.877	233.8	389.9	156.1	1.0398	1.3456
52	94.50	79.80	0.03111	1.10	4.294	0.909	234.9	390.4	155.4	1.0421	1.3453
54	97.5	82.80	0.03121	1.07	4.281	0.935	236.1	390.8	154.7	1.0443	1.3450
56	100.6	85.9	0.03130	1.04	4.267	0.962	237.3	391.3	154.0	1.0466	1.3447
58	103.7	89.0	0.03140	1.01	4.254	0.990	238.5	391.7	153.3	1.0488	1.3444

[a] Inches of mercury vacuum.

(Continued on Page 266)

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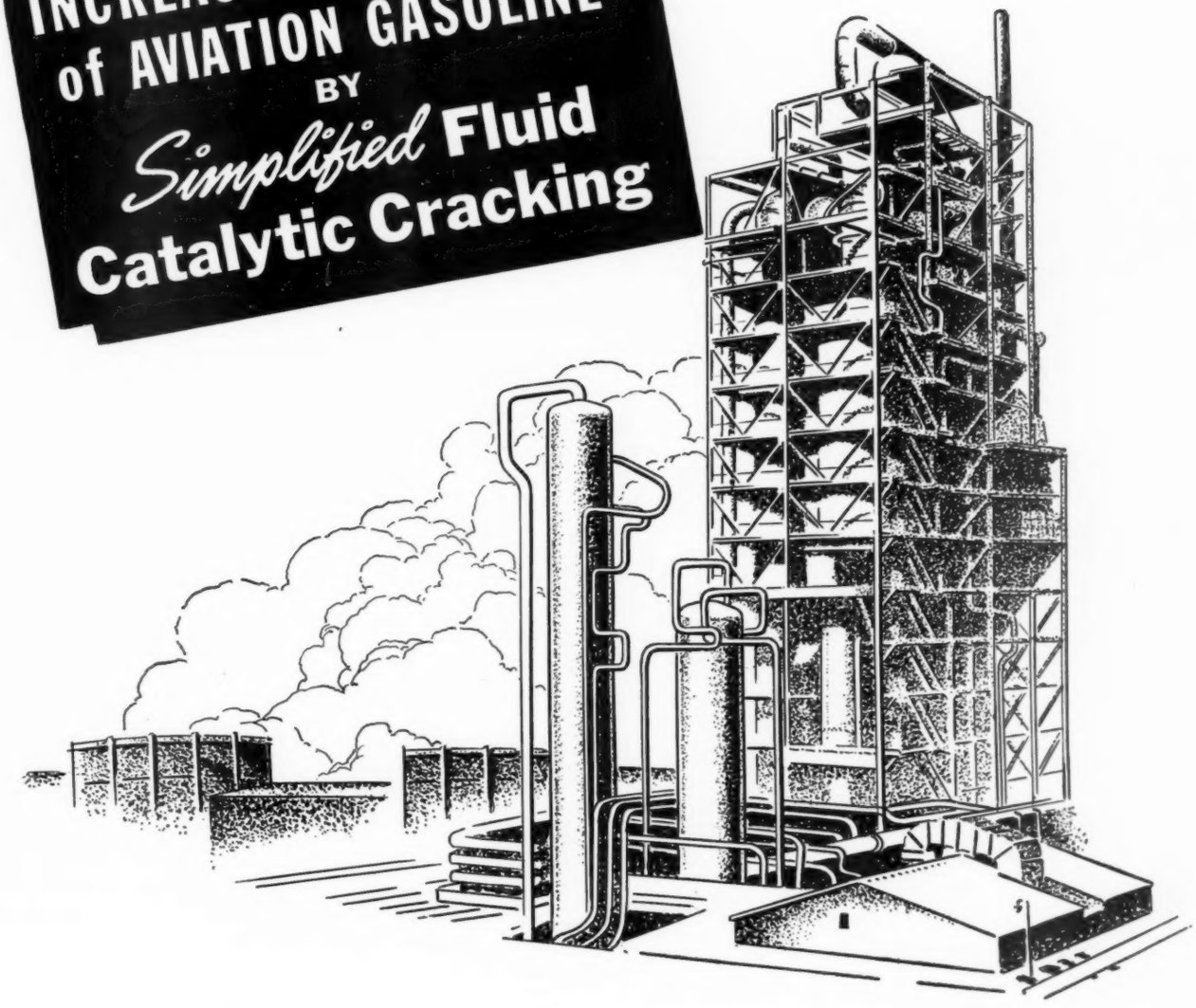

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TABLE I

Temperature data for saturated propane (concluded)

Temperature t, °F.	Pressure, Lb./Sq. In. Absolute, P	Pressure, Lb./Sq. In. Gage, gp	Volume, Cu. Ft./Lb. Liquid v	Volume, Cu. Ft./Lb. Vapor V	Density Liquid $(1/v)$, lb./gal.	Density Vapor $(1/V)$, lb./cu. ft.	Heat Content, B. T. U./Lb. Liquid h	Heat Content, B. T. U./Lb. Vapor H	Latent Heat L, B. T. U./Lb.	Entropy, B. T. U./Lb./° F. Liquid s	Entropy, B. T. U./Lb./° F. Vapor S
60	106.9	92.2[a]	0.03150	0.984	4.240	1.016	239.6	392.2	152.6	1.0511	1.3441
62	110.2	95.5	0.03162	0.958	4.226	1.044	240.8	392.7	151.8	1.0534	1.3438
64	113.6	98.9	0.03174	0.932	4.213	1.073	242.0	393.1	151.1	1.0556	1.3435
66	117.1	102.4	0.03185	0.906	4.199	1.104	243.2	393.5	150.3	1.0579	1.3433
68	120.6	105.9	0.03197	0.880	4.186	1.136	244.4	394.0	149.5	1.0601	1.3430
70	124.3	109.6	0.03209	0.854	4.172	1.171	245.7	394.4	148.7	1.0624	1.3427
72	127.9	113.2	0.03221	0.832	4.158	1.202	246.9	394.8	147.8	1.0647	1.3424
74	131.7	117.0	0.03233	0.810	4.144	1.235	248.1	395.2	147.0	1.0669	1.3421
76	135.6	120.9	0.03245	0.788	4.131	1.269	249.4	395.6	146.2	1.0692	1.3419
78	139.6	124.9	0.03257	0.766	4.117	1.305	250.2	396.0	145.4	1.0714	1.3416
80	143.6	128.9	0.03269	0.745	4.103	1.342	251.9	396.4	144.5	1.0737	1.3413
82	147.7	133.0	0.03281	0.725	4.088	1.379	253.1	396.8	143.7	1.0760	1.3410
84	151.8	137.1	0.03293	0.704	4.074	1.420	254.4	397.2	142.8	1.0782	1.3408
86	156.2	141.5	0.03305	0.684	4.059	1.462	255.6	397.6	141.9	1.0805	1.3405
88	160.6	145.9	0.03317	0.663	4.045	1.508	256.9	398.0	141.0	1.0827	1.3403
90	165.0	150.3	0.03329	0.643	4.030	1.555	258.2	398.3	140.1	1.0850	1.3400
92	169.6	154.9	0.03341	0.626	4.015	1.597	259.5	398.7	139.2	1.0873	1.3398
94	174.2	159.5	0.03353	0.609	4.001	1.642	260.8	399.1	138.3	1.0895	1.3395
96	178.9	164.2	0.03366	0.592	3.986	1.689	262.1	399.5	137.4	1.0918	1.3393
98	183.7	169.0	0.03378	0.575	3.972	1.739	263.3	399.9	136.5	1.0940	1.3390
100	188.7	174.0	0.03390	0.558	3.957	1.792	264.6	400.2	135.6	1.0963	1.3388
102	193.8	179.1	0.03402	0.544	3.941	1.838	265.9	400.5	134.6	1.0986	1.3386
104	198.9	184.2	0.03415	0.530	3.925	1.887	267.2	400.9	133.7	1.1010	1.3384
106	204.1	189.4	0.03427	0.516	3.910	1.938	268.5	401.2	132.7	1.1033	1.3382
108	209.3	194.6	0.03439	0.502	3.894	1.992	269.8	401.6	131.8	1.1057	1.3380
110	214.8	200.1	0.03452	0.487	3.878	2.053	271.1	401.9	130.8	1.1080	1.3378
112	220.4	205.7	0.03468	0.475	3.862	2.105	272.5	402.3	129.8	1.1103	1.3376
114	226.0	211.3	0.03484	0.463	3.846	2.160	273.9	402.7	128.8	1.1126	1.3374
116	231.6	216.9	0.03500	0.451	3.830	2.217	275.2	403.0	127.8	1.1149	1.3372
118	237.3	222.6	0.03516	0.439	3.814	2.278	276.6	403.4	126.8	1.1172	1.3370
120	243.4	228.7	0.03532	0.426	3.798	2.347	278.0	403.8	125.8	1.1195	1.3368
122	249.7	235.0	0.03548	0.415	3.780	2.410	279.4	404.1	124.7	1.1218	1.3366
124	255.7	241.0	0.03564	0.404	3.763	2.475	280.9	404.5	123.6	1.1241	1.3363
126	261.7	247.0	0.03580	0.393	3.745	2.544	282.3	404.8	122.5	1.1264	1.3361
128	267.9	253.2	0.03596	0.382	3.728	2.618	283.8	405.2	121.4	1.1287	1.3358
130	274.5	259.8	0.03612	0.370	3.710	2.703	285.2	405.4	120.2	1.1310	1.3356
132	281.1	266.4	0.03630	0.360	3.692	2.778	286.7	405.7	119.0	1.1334	1.3353
134	287.9	273.2	0.03648	0.350	3.674	2.857	288.2	406.1	117.9	1.1358	1.3350
136	294.7	280.0	0.03666	0.340	3.657	2.941	289.7	406.4	116.7	1.1382	1.3348
138	301.4	286.7	0.03684	0.330	3.639	3.030	291.2	406.7	115.5	1.1406	1.3345
140	308.4	293.7	0.03702	0.320	3.621	3.125	292.7	407.0	114.3	1.1430	1.3347
142	315.5	300.8	0.03725	0.312	3.600	3.205	294.2	407.3	113.1	1.1454	1.3339
144	322.8	308.1	0.03748	0.303	3.578	3.300	295.7	407.6	111.9	1.1479	1.3336
146	330.2	315.5	0.03771	0.295	3.557	3.390	297.2	407.8	110.6	1.1503	1.3332
148	337.6	322.9	0.03794	0.286	3.535	3.496	298.6	408.0	109.4	1.1528	1.3329
150	345.4	330.7	0.03817	0.278	3.514	3.597	300.2	408.2	108.0	1.1552	1.3326
152	352.9	338.2	0.03846	0.270	3.487	3.704	301.8	408.4	106.6	1.1578	1.3321
154	360.8	346.1	0.03875	0.263	3.460	3.802	303.4	408.6	105.2	1.1603	1.3317
156	368.6	353.9	0.03904	0.255	3.434	3.922	305.1	408.7	103.6	1.1629	1.3312
158	376.6	361.9	0.03933	0.248	3.407	4.032	306.8	408.8	102.0	1.1654	1.3308
160	385.0	370.3	0.03962	0.240	3.380	4.167	308.4	408.8	100.4	1.1680	1.3303
162	392.9	378.2	0.03996	0.234	3.351	4.273	310.2	408.8	98.6	1.1707	1.3297
164	401.0	386.3	0.04030	0.227	3.322	4.405	312.0	408.9	96.9	1.1734	1.3291
166	409.3	394.6	0.04064	0.221	3.292	4.525	313.9	408.9	95.0	1.1762	1.3284
168	417.8	403.1	0.04098	0.214	3.263	4.673	315.7	408.8	93.1	1.1789	1.3278
170	426.0	411.3	0.04132	0.208	3.234	4.808	317.5	408.6	91.1	1.1816	1.3272
172	436.4	421.7	0.04179	0.202	3.201	4.950	319.5	408.6	89.1	1.1847	1.3262
174	445.9	431.2	0.04226	0.197	3.168	5.076	321.5	408.6	87.1	1.1878	1.3252
176	455.2	440.5	0.04273	0.191	3.136	5.236	323.5	408.4	84.9	1.1908	1.3243
178	464.1	449.4	0.04320	0.186	3 103	5.376	325.5	408.2	82.7	1.1939	1.3233
180	473.2	458.5	0.04367	0.180	3.07	5.556	327.5	407.6	80.1	1.1970	1.3223
182	483.0	468.3	0.04436	0.174	3.03	5.747	329.8	407.4	77.6	1.2004	1.3210
184	492.9	478.2	0.04505	0.168	2.99	5.952	332.2	407.1	74.9	1.2038	1.3196
186	503.1	488.4	0.04574	0.161	2.95	6.211	334.5	406.6	72.1	1.2072	1.3183
188	512.8	498.1	0.04643	0.155	2.91	6.452	336.9	405.9	69.0	1.2106	1.3169
190	523.4	508.7	0.04712	0.149	2.87	6.711	339.2	404.6	65.7	1.2140	1.3156
200	575.0	560.3	0.0521	0.113	2.59	8.850	353.5	398.3	44.8	1.2360	1.3040

[a] Inches of mercury vacuum.

(Continued from Page 263)

of them deviate from the smooth curve by amounts that indicate a strong possibility that the tabulated values were either misread from the original chart or that a typographical error had been made.

These values were smoothed as indicated; in addition, the deviation of the saturated specific volumes from those calculated from the simple gas law were plotted as unique or limiting values for the compressibility factors at any given temperature. The compressibility factors were then interpolated and extrapolated for the vapor to cover the whole range above —70°F.

Except in the case of the saturated liquid, the data substantially below 86°F. may be considered purely imaginative, without experimental basis. Actually, the curves drawn are merely similar to those in the known experimental regions, and the accuracy of these values must be judged in the light of their agreement or disagreement with other experimental data.

From the compressibility factors as plotted above, the corresponding isobars were plotted and their slopes accurately evaluated; the corresponding values for $(\partial Z/\partial T)_P$ were plotted against pressure.

From the smoothed values the isothermal change of enthalpy with pressure was calculated at constant temperature by the well-known formula:

$$\left[\frac{\partial H}{\partial P}\right]_T = \frac{-NRT^2}{P}\left[\frac{\partial Z}{\partial T}\right]_P$$

The values of the function —H at constant temperature are obtained by graphical integration of the values for the change in enthalpy with pressure at constant temperature when plotted against absolute pressure.

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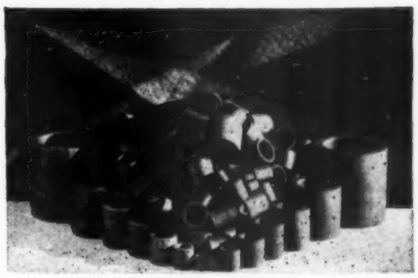

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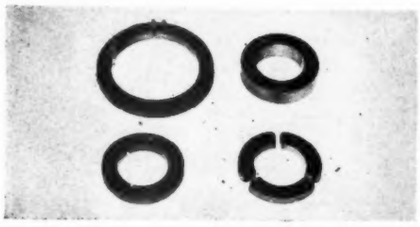

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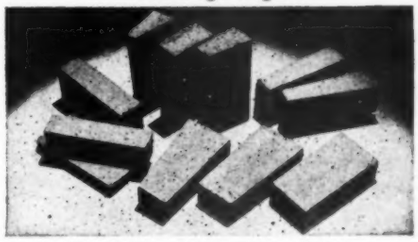

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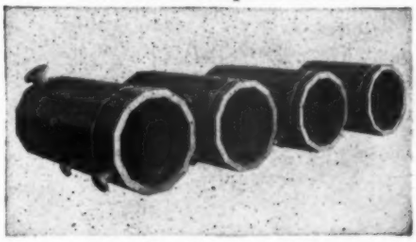

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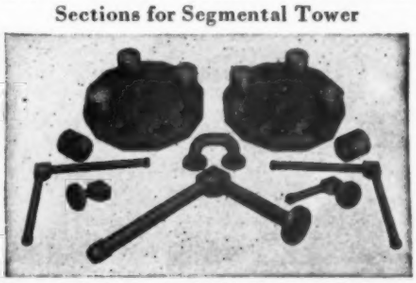

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The agreement between our values for 190°F. and those of Deschner and Brown for 194°F. is striking. The disagreement between our 160° values and those of Deschner and Brown at 158°F. is substantial; but as errors occur in their tabulated figures for this range, the results of the correlation weigh strongly in favor of our 160° figures.

In the field of specific heat of propane vapor, the values in the literature have no satisfactory agreement.

The values of Edmister[5] are based on a correlation and have no independent value unless confirmed by experimental data. This is particularly true in the case of propane, which deviates substantially in most correlations.

The values of Kistiakowsky and Rice[7] for propane have no confirmation from other sources. Their experimental values for other gases obtained with the same equipment have had substantial confirmation, however, and this correlation also checks their data. When used as a basis for calculation of the absolute enthalpy values, their values give extremely good agreement with heat content data for the saturated liquid over the whole range of experimental work.

The values of Dobratz[4] are based on assumptions concerning certain potential barriers producing hindered rotation of the methyl groups in this compound; he gives different data for different assumed values of this potential barrier.

On this basis we have assumed that the data of Kistiakowsky and Rice[7] are correct. As a matter of fact, no other values will produce a satisfactory correlation, and the correlation indicates that they are probably accurate to about one in the third decimal place.

Correlation of Results

Absolute enthalpy. Fig. 1 gives the first correlation of data. The reference value for the heat content of the saturated liquid at atmospheric pressure was obtained by graphical integration of the specific heat values of Kemp and Egan between absolute zero and the boiling point at atmospheric pressure. Therefore, these data give the enthalpy of propane above the solid at absolute zero and are based on the assumption that the entropy at this point is zero.

From this reference value for the liquid and from the specific heats, specific volumes, and latent heats previously discussed, the saturated liquid and saturated vapor curve was calculated. From a reference point at —40°F. on the saturated vapor line, H_0 was calculated at —40°F. and infinite dilution from our —ΔH data. From this point the absolute values were calculated for the heat content at infinite dilution at various temperatures between —70° and +200°F. from the data of Kistiakowsky and Rice as extrapolated. From these reference values and the —ΔH data previously calculated, the absolute heat contents at various temperatures and pressures were obtained. Then the extension of the lines showing the change in enthalpy with pressure at constant temperature, as expressed in absolute values, agrees with the values on the saturated vapor curve within 0.2 B.t.u. in most cases.

Over the range from —40° to +200°F., independent of the interpolations and extrapolations on the compressibility chart, the values of Kistiakowsky and Rice are in good agreement, as —ΔH at —40°F. is rela-

TABLE 2
Properties* of superheated propane vapor

Temp. °F.	P = 15 In. Hg, t = −70.6° F.			P = 10 In. Hg, t = −60° F.			P = 5 In. Hg, t = −51° F.		
	V	H	S	V	H	S	V	H	S
Satd.	12.72	356.5	1.3785	9.80	360.0	1.3740	7.90	362.75	1.3718
−70	12.78	357.0	1.3791	....	...	....	....	...	....
−60	13.11	360.3	1.3869	....	...	....	....	...	....
−50	13.45	363.5	1.3946	10.042	363.2	1.3816	7.978	362.8	1.3720
−40	13.79	366.8	1.4023	10.30	366.5	1.3893	8.182	366.2	1.3796
−30	14.13	370.1	1.4100	10.55	369.8	1.3970	8.387	369.6	1.3872
−20	14.47	373.4	1.4177	10.81	373.1	1.4045	8.591	373.0	1.3948
−10	14.81	376.8	1.4253	11.06	376.6	1.4121	8.796	376.4	1.4024
0	15.14	380.2	1.4329	11.321	380.0	1.4197	9.000	379.9	1.4100
10	15.48	383.8	1.4405	11.57	383.6	1.4273	9.204	383.4	1.4176
20	15.82	387.4	1.4481	11.83	387.2	1.4349	9.409	387.0	1.4252
30	16.16	391.1	1.4557	12.08	390.9	1.4425	9.613	390.7	1.4328
40	16.50	394.8	1.4633	12.34	394.6	1.4501	9.818	394.4	1.4404
50	16.83	398.6	1.4709	12.59	398.4	1.4577	10.02	398.2	1.4480
60	17.17	402.4	1.4785	12.85	402.2	1.4652	10.23	402.0	1.4556
70	17.51	406.3	1.4861	13.10	406.1	1.4727	10.43	406.0	1.4630
80	17.85	410.2	1.4937	13.36	410.0	1.4802	10.64	410.0	1.4706
90	18.19	414.3	1.5013	13.61	414.1	1.4877	10.84	414.0	1.4780
100	18.52	418.4	1.5088	13.87	418.2	1.4952	11.050	418.1	1.4854
110	18.86	422.5	1.5162	14.12	422.3	1.5026	11.25	422.1	1.4928
120	19.20	426.6	1.5235	14.38	426.4	1.5101	11.45	426.2	1.5002
130	19.54	430.8	1.5308	14.63	430.6	1.5174	11.66	430.6	1.5075
140	19.88	435.2	1.5380	14.89	435.0	1.5245	11.86	435.9	1.5148
150	20.21	439.6	1.5452	15.14	439.4	1.5317	12.07	439.3	1.5221
160	20.55	444.1	1.5524	15.40	443.9	1.5389	12.27	443.8	1.5293
170	20.89	448.6	1.5596	15.65	448.4	1.5461	12.47	448.4	1.5365
180	21.23	453.1	1.5668	15.91	452.9	1.5533	12.68	452.9	1.5437
190	21.57	457.9	1.5740	16.16	457.7	1.5605	12.88	457.6	1.5509
200	21.90	462.5	1.5812	16.42	462.4	1.5677	13.09	462.4	1.5581

	P = 14.696 Lb. Abs., t = −43.708° F.			P = 16 Lb. Abs., t = −40.01° F.			P = 20 Lb. Abs., t = −30.30° F.		
	V	H	S	V	H	S	V	H	S
Satd.	6.66	364.6	1.3681	6.195	365.5	1.3670	5.050	368.4	1.3640
−40	6.775	365.8	1.3710	6.212	365.6	1.3671	....	...	....
−30	6.949	369.3	1.3788	6.371	369.2	1.3784	5.060	368.6	1.3642
−20	7.123	372.8	1.3866	6.530	372.6	1.3825	5.186	372.2	1.3719
−10	7.297	376.3	1.3943	6.659	376.1	1.3902	5.313	375.8	1.3796
0	7.471	379.8	1.4020	6.848	379.6	1.3979	5.439	739.3	1.3873
10	7.644	383.3	1.4096	7.007	383.2	1.4056	5.567	382.9	1.3949
20	7.816	386.8	1.4772	7.166	386.8	1.4132	5.695	386.5	1.4025
30	7.988	390.6	1.4248	7.324	390.4	1.4208	5.823	390.2	1.4101
40	8.160	394.3	1.4324	7.482	394.2	1.4284	5.951	393.9	1.4177
50	8.332	398.1	1.4399	7.640	398.0	1.4359	6.079	397.7	1.4252
60	8.503	401.9	1.4474	7.798	401.8	1.4434	6.207	401.6	1.4327
70	8.674	405.8	1.4549	7.955	405.8	1.4508	6.334	405.5	1.4402
80	8.844	409.8	1.4623	8.112	409.8	1.4582	6.461	409.4	1.4477
90	9.016	413.9	1.4698	8.269	413.8	1.4656	6.588	413.5	1.4551
100	9.187	418.0	1.4772	8.426	417.9	1.4730	6.716	417.6	1.4625
110	9.358	422.1	1.4845	8.583	421.9	1.4804	6.843	421.7	1.4698
120	9.528	426.2	1.4918	8.740	426.1	1.4878	6.969	425.9	1.4771
130	9.699	430.4	1.4991	8.897	430.4	1.4952	7.095	430.2	1.4844
140	9.869	434.8	1.5064	9.054	434.8	1.5026	7.221	434.6	1.4917
150	10.040	439.2	1.5137	9.211	439.2	1.5099	7.347	439.0	1.4990
160	10.21	443.7	1.5210	9.368	443.7	1.5172	7.473	443.5	1.5063
170	10.38	448.3	1.5283	9.525	448.2	1.5245	7.599	448.0	1.5136
180	10.51	452.9	1.5256	9.682	452.8	1.5317	7.725	452.6	1.5209
190	10.72	457.5	1.5428	9.839	457.4	1.5389	7.851	457.3	1.5282
200	10.84	462.4	1.5500	9.996	462.2	1.5460	7.977	461.9	1.5355

	P = 24 Lb. Abs., t = −21.97° F.			P = 30 Lb. Abs., t = −11.52° F.			P = 40 Lb. Abs., t = +2.90° F.		
	V	H	S	V	H	S	V	H	S
Satd.	4.25	370.9	1.3615	3.30	374.00	1.3588	2.61	378.2	1.3548
−20	4.279	371.7	1.3632	....	....	....	....	...	....
−10	4.390	375.3	1.3712	3.47	374.6	1.3597	....	...	....
0	4.499	378.9	1.3790	3.559	378.3	1.3678	....	...	....
10	4.608	382.5	1.3806	3.647	382.0	1.3754	2.684	380.9	1.3603
20	4.716	386.2	1.3942	3.735	385.7	1.3830	2.753	384.7	1.3684
30	4.824	389.9	1.4018	3.823	389.4	1.3905	2.821	388.5	1.3761
40	4.932	393.6	1.4094	3.911	393.1	1.3980	2.889	392.2	1.3838
50	5.040	397.4	1.4170	3.999	396.9	1.4055	2.957	396.1	1.3914
60	5.147	401.3	1.4245	4.087	400.8	1.4130	3.025	400.0	1.3990
70	5.254	405.2	1.4320	4.174	404.7	1.4205	3.092	404.0	1.4065
80	5.361	409.2	1.4394	4.261	408.7	1.4280	3.159	408.0	1.4140
90	5.467	413.3	1.4468	4.347	412.8	1.4354	3.224	412.1	1.4215
100	5.573	417.4	1.4542	4.432	417.0	1.4428	3.289	416.2	1.4290
110	5.679	421.5	1.4616	4.517	421.2	1.4502	3.354	420.4	1.4365
120	5.785	425.6	1.4690	4.602	425.4	1.4576	3.419	424.6	1.4440
130	5.891	429.8	1.4764	4.687	429.6	1.4650	3.484	429.0	1.4514
140	5.997	434.3	1.4837	4.772	434.0	1.4724	3.549	433.4	1.4588
150	6.103	438.8	1.4910	4.857	438.4	1.4898	3.614	437.9	1.4662
160	6.209	443.3	1.4983	4.942	443.0	1.4872	3.679	442.5	1.4736
170	6.315	447.9	1.5056	5.027	447.6	1.4946	3.744	447.1	1.4810
180	6.420	452.5	1.5128	5.112	452.2	1.5020	3.809	451.8	1.4884
190	6.525	457.1	1.5200	5.197	456.9	1.5094	3.874	456.5	1.4957
200	6.630	462.0	1.5272	5.282	461.8	1.5168	3.939	461.3	1.5030

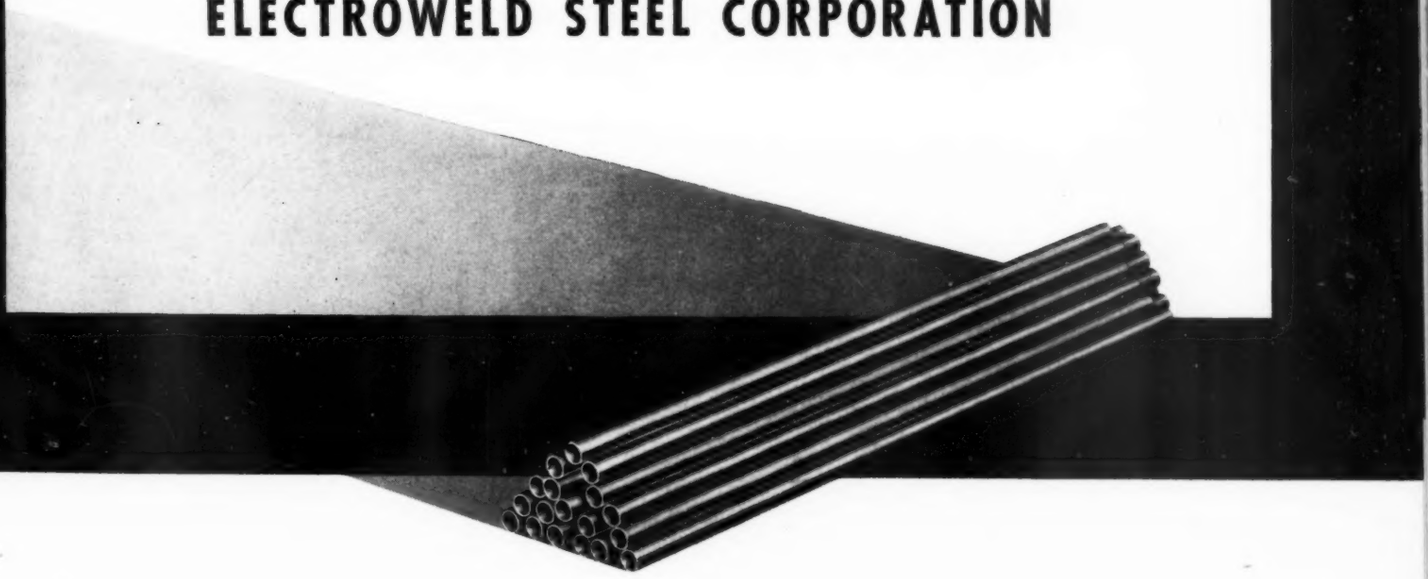
*See Page 270

TALON, INC.

Steel Tube Division

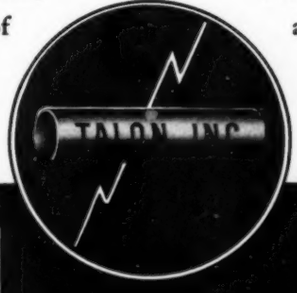
Successors to

ELECTROWELD STEEL CORPORATION



TALON STEEL TUBE DIVISION manufactures pressure and mechanical tubing on most modern and up-to-date equipment. These excellent production facilities, plus scrupulous care by skilled workmen during each operation, give you assurance that every length of tubing is uniform and has these important high qualities: uniform diameter, uniform wall thickness, uniformity of structure in the weld area, plus square and uniform cuts which permit savings of real importance.

Talon's Steel Tube Division has a substantial capacity devoted entirely to the war effort . . . another mill, now under construction, will increase even further Talon's production of steel tubes. When victory be ours, we believe that this excellent product will prove advantageous in your peacetime production operations. . . . . .



TALON . . . . . INC.

STEEL TUBE DIVISION **OIL CITY, PENNA.**

TABLE 2
Properties* of superheated propane vapor (concluded)

Temp.	P = 50 Lb. Abs., t = 14.7° F.			P = 60 Lb. Abs., t = 24.80° F.			P = 80 Lb. Abs., t = 41.69° F		
° F.	V	H	S	V	H	S	V	H	S
Satd.	2.115	381.2	1.3521	1.76	383.8	1.3501	1.32	387.8	1.3470
20	2.159	383.5	1.3562	....	...	....	....	...	....
30	2.217	387.4	1.3647	1.814	386.1	1.3547	....	...	....
40	2.275	391.3	1.3726	1.863	390.1	1.3630	....	...	....
50	2.331	395.2	1.3804	1.911	394.1	1.3710	1.36	391.9	1.3540
60	2.386	399.1	1.3881	1.959	398.2	1.3789	1.424	396.1	1.3624
70	2.441	403.1	1.3957	2.006	402.2	1.3808	1.462	400.3	1.3707
80	2.495	407.1	1.4033	2.053	406.3	1.3948	1.500	404.6	1.3785
90	2.549	411.2	1.4109	2.099	410.5	1.4025	1.537	408.9	1.3863
100	2.602	415.4	1.4185	2.145	414.8	1.4102	1.573	413.2	1.3940
110	2.656	419.6	1.4261	2.190	419.0	1.4179	1.609	417.5	1.4017
120	2.709	423.9	1.4337	2.235	423.4	1.4254	1.644	421.8	1.4094
130	2.762	428.3	1.4412	2.280	427.8	1.4330	1.679	426.3	1.4171
140	2.815	432.8	1.4487	2.325	432.2	1.4404	1.714	430.9	1.4248
150	2.868	437.3	1.4562	2.370	436.8	1.4479	1.749	435.6	1.4325
160	2.921	441.9	1.4637	2.415	441.4	1.4554	1.784	440.3	1.4402
170	2.975	446.6	1.4711	2.460	446.1	1.4629	1.818	445.0	1.4478
180	3.027	451.3	1.4785	2.505	450.8	1.4703	1.852	449.8	1.4554
190	3.079	456.1	1.4859	2.549	455.6	1.4777	1.886	454.7	1.4629
200	3.131	460.9	1.4933	2.593	460.5	1.4851	1.920	459.7	1.4704
	P = 100 Lb. Abs., t = 55.62° F.			P = 130 Lb. Abs., t = 73.20° F.			P = 160 Lb. Abs., t = 87.71° F.		
Satd.	1.06	391.2	1.3448	0.8165	395.0	1.3424	0.6685	397.9	1.3404
60	1.094	393.5	1.3488	....	...	....	....	...	....
70	1.131	398.3	1.3573	....	...	....	....	...	....
80	1.164	402.6	1.3656	0.8456	398.8	1.3486	....	...	....
90	1.196	406.9	1.3735	0.8762	403.6	1.3571	0.6695	399.2	1.3423
100	1.227	411.4	1.3816	0.9045	408.3	1.3659	0.6969	404.7	1.3521
110	1.258	415.7	1.3893	0.9315	412.9	1.3740	0.7222	409.6	1.3610
120	1.289	420.3	1.3962	0.9588	417.8	1.3822	0.7464	414.6	1.3698
130	1.318	424.9	1.4050	0.9815	420.7	1.3903	0.7691	419.7	1.3784
140	1.347	429.6	1.4130	1.006	425.7	1.3987	0.7908	424.8	1.3867
150	1.375	434.4	1.4209	1.029	430.7	1.4059	0.8118	429.9	1.3949
160	1.400	439.1	1.4286	1.052	435.7	1.4150	0.8319	434.9	1.4031
170	1.432	444.0	1.4362	1.076	440.7	1.4230	0.8520	440.0	1.4113
180	1.460	448.8	1.4440	1.098	445.3	1.4310	0.8712	445.1	1.4195
190	1.488	453.8	1.4518	1.120	450.9	1.4389	0.8903	450.9	1.4276
200	1.516	458.8	1.4598	1.143	456.1	1.4468	0.9093	456.1	1.4357
	P = 190 Lb. Abs., t = 100.50° F.			P = 220 Lb. Abs., t = 111.85° F.			P = 250 Lb. Abs., t = 122.12° F.		
Satd.	0.5540	400.4	1.3388	0.4738	402.5	1.3375	0.4130	404.2	1.3355
110	0.5774	405.9	1.3485	....	...	....	....	...	....
120	0.5995	410.4	1.3580	0.4911	407.7	1.3460	....	...	....
130	0.6208	415.9	1.3670	0.5121	413.7	1.3558	0.4283	409.7	1.3450
140	0.6415	421.1	1.3759	0.5314	419.2	1.3650	0.4473	415.9	1.3550
150	0.6607	426.4	1.3844	0.5498	424.5	1.3739	0.4649	421.4	1.3640
160	0.6792	431.5	1.3930	0.5673	429.7	1.3827	0.4816	427.1	1.3732
170	0.6971	437.0	1.4013	0.5846	435.3	1.3913	0.4972	432.6	1.3819
180	0.7144	442.2	1.4096	0.5998	440.6	1.3999	0.5121	438.0	1.3908
190	0.7311	447.5	1.4176	0.6149	445.9	1.4080	0.5266	443.5	1.3990
200	0.7472	452.7	1.4255	0.6302	451.2	1.4161	0.5408	448.9	1.4074
	P = 300 Lb. Abs., t = 137.55° F.								
Satd.	0.3332	406.6	1.3345						
140	0.3392	408.7	1.3372						
150	0.3579	415.6	1.3480						
160	0.3745	422.0	1.3580						
170	0.3896	427.8	1.3674						
180	0.4037	433.2	1.3765						
190	0.4171	439.2	1.3855						
200	0.4303	444.9	1.3944						

* Pressures below atmospheric are expressed in inches of Hg vacuum pressures; above atmospheric, in pounds per square inch absolute.

tively small. However, the values obtained from the compressibility chart correlate well with the other data.

Specific heats of the vapor at constant pressure for 0 lb. absolute were taken from Kistiakowsky and Rice; and for the higher pressures, they were read from the heat content chart.

Entropy-temperature. Fig. 2 gives a second correlation of data. The reference value for the entropy of the liquid at its boiling point was taken from the experimental values of Kemp and Egan. The saturated liquid and saturated vapor curves were then calculated in the conventional manner. The lines of constant quality, expressed as percent vapor, were calculated directly from these values. The lines of constant pressure in the superheat region were calculated from our values for the specific heat of the vapor at constant pressure. The lines of constant volume were calculated from the compressibility chart and plotted against the temperature coördinate and the pressure parameters. The enthalpy parameters were read from the heat content chart and plotted in the same manner.

All data are reported on the B.t.u.-°F.-lb. system, except as noted. The actual molecular weights employed by each author were used in calculating data from the molal basis, and in each case the author's value for the absolute temperature was used in calculating the Fahrenheit temperature. The data of Deschner and Brown were corrected for ethane content of their sample. H signifies the absolute enthalpy referred to the solid at absolute zero. S refers to absolute entropy on the same basis, V is in cu. ft. per lb. units, and J is taken as 0.18511.

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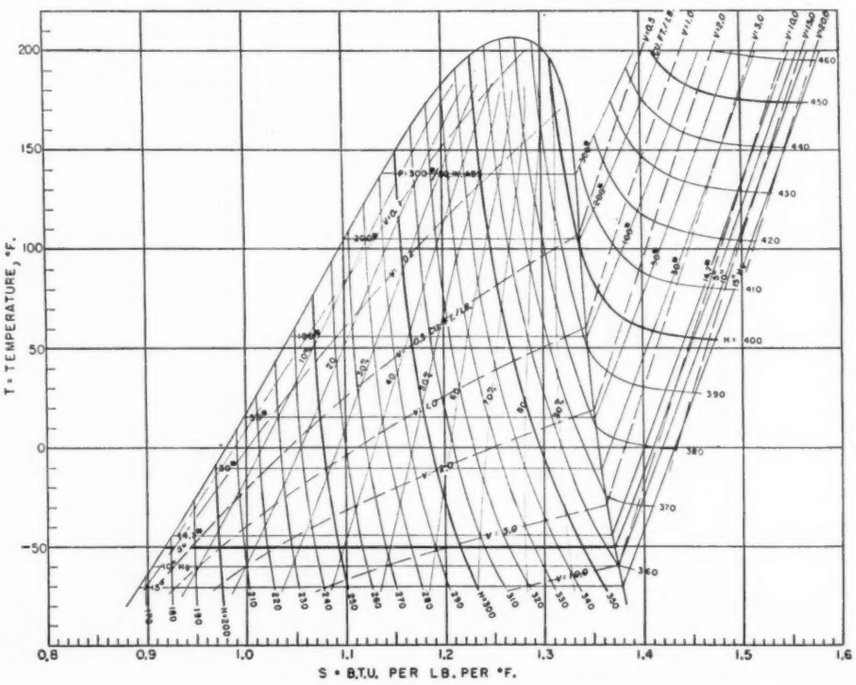


Fig. 2. Entropy-temperature chart for propane

Normal Butane*

By R. C. ALDEN
Phillips Petroleum Company

AT this time, with *iso*butane so much in the forefront, some explanation should be given for choosing to discuss normal butane. With the advent of butane isomerization processes *iso*butane and normal butane are becoming almost synonymous. If, as some seem to think, there is to be a shortage of *iso*butane, attention must then be focused on normal butane. It is further of significance to note that the tremendous refinery uses of C^4 hydrocarbons are bringing about a definite problem in motor fuel volatility. Propane as a substitute for butane in motor fuel is under serious consideration in many places. All of these trends provide incentive for natural gasoline manufacturers to increase C_4 extraction at natural gasoline plants. Normal butane may become as important as *iso*butane has already become.

Referring to the processes for the manufacture of aviation gasoline from light hydrocarbons it is characteristic of them that a large portion of their investment and critical material usage is for the fractionation of the light hydrocarbons. The *deiso*butanizer or "butane splitter" is a substantial part of the investment in butane isomerization plants, in alkylation plants and in codimer plants. Thus any natural gasoline manufacturer who is seriously considering a "butane splitter" for the segregation of field *iso*butane should also study the amplification of his project to include at least butane isomerization and perhaps alkylate or codimer production.

To illustrate the point made in the preceding paragraph simplified flow diagrams of four process arrangements are shown in Fig. 1. In each case, C_4 and lighter from natural gasoline is the entire feed to the system.

In these four diagrams each succeeding one is identical to its predecessor except for the addition of one or more operations. The sizes of the various units, of course, will depend on the successive operations.

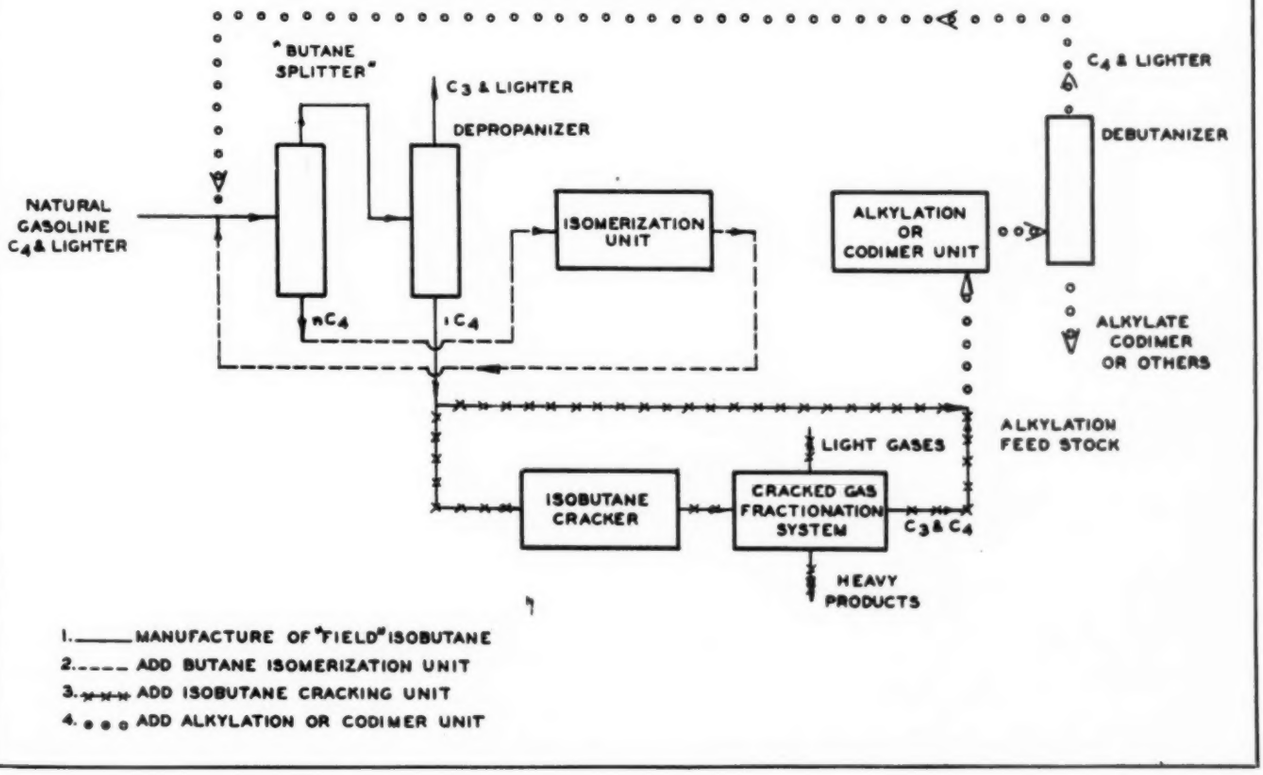
In Fig. 1 the solid flow lines represent the simple case of the segregation of *iso*butane from natural gasoline C_4's and lighter. Equipment requirements are a "butane splitter" and a depropanizer. The operation segregates the feed into three streams; *iso*butane, normal butane and propane and lighter.

The dashed flow lines in Fig. 1 represent the flow diagram for the addition of a butane isomerization unit to the system previously described. To the equipment has been added an isomerization unit to which is fed normal butane from the "butane splitter" and whose output is added to the feed of the "butane splitter." Obviously, the columns will have to be increased in size, but the fractionation steps are the same. In this operation two products are made, *iso*butane and propane and lighter.

It is a rare thing for an adequate olefin-bearing stream to be available to a field natural gasoline situation. The crossed flow lines in Fig. 1 represent the addition of an *iso*butane cracker to the equipment already provided. All or a portion of the *iso*butane from the depropanizer is fed to the *iso*butane cracker. In the cracker the *iso*butane is cracked to a depth of 20 to 30 percent. The C_3-C_4 content of the cracked gas is ideal for feed to a codimer plant or mixed with uncracked *iso*butane is ideal feed for an alkylation unit. In the event neither of these units is installed the product should be of interest to re-

*Presented before Natural Gasoline Association of America, Dallas, Texas, April 14-16, 1943.

Fig. 1. Aviation gasoline products in a natural gasoline situation



finers with alkylation or codimer facilities.

As a final step, the circle lines in Fig. 1 show flow for the addition of an alkylation or codimer unit. In the case of a codimer unit all the *iso*butane from the depropanizer would be charged to the *iso*butane cracker. In the case of an alkylation unit only a portion goes to the *iso*butane cracker. The effluent of the conversion unit passes to a debutanizer whose kettle product is the alkylate or codimer. The overhead C_4's and lighter is fed to the "butane splitter" (or to the depropanizer or to the conversion unit feed or to any combination of these three).

Of particular interest in this sequence of flow diagrams is that portion of Fig. 1 which shows the *iso*butane cracker since this provides an olefin bearing stream for subsequent conversion operations. The flow diagram for this operation together with the flow for the codimer plant is shown in somewhat greater detail in Fig. 2, which is self-explanatory.

Phillips Petroleum Company has had in operation for five years a plant in which *iso*butane is thermally cracked to produce propylene and *iso*butylene. The cracking unit consists of a gas fired furnace containing an all welded coil of 4-in. O.D. by 3½-in. I.D. 18-8 chrome nickel alloy tubing having an aggregate length of 2511 ft.

Operating temperatures have been in the range 1200°F. to 1350°F.; usual flow rates have been from 75,000 to 125,000 gal. of *iso*butane per day; and pressures have been in the range 60 to 80 lb. per sq. in. ga.

Conversion of *iso*butane per pass through the cracking coil has been approximately 25 percent. Ultimate yield of *iso*butylene per 100 lb. of *iso*butane destroyed has been about 50 lb. In addition about 25 lb. of propylene have been obtained, making the total yield of useful olefins 75 lb. per 100 lb. of *iso*butane cracked. A considerable quantity of hydrogen is also produced.

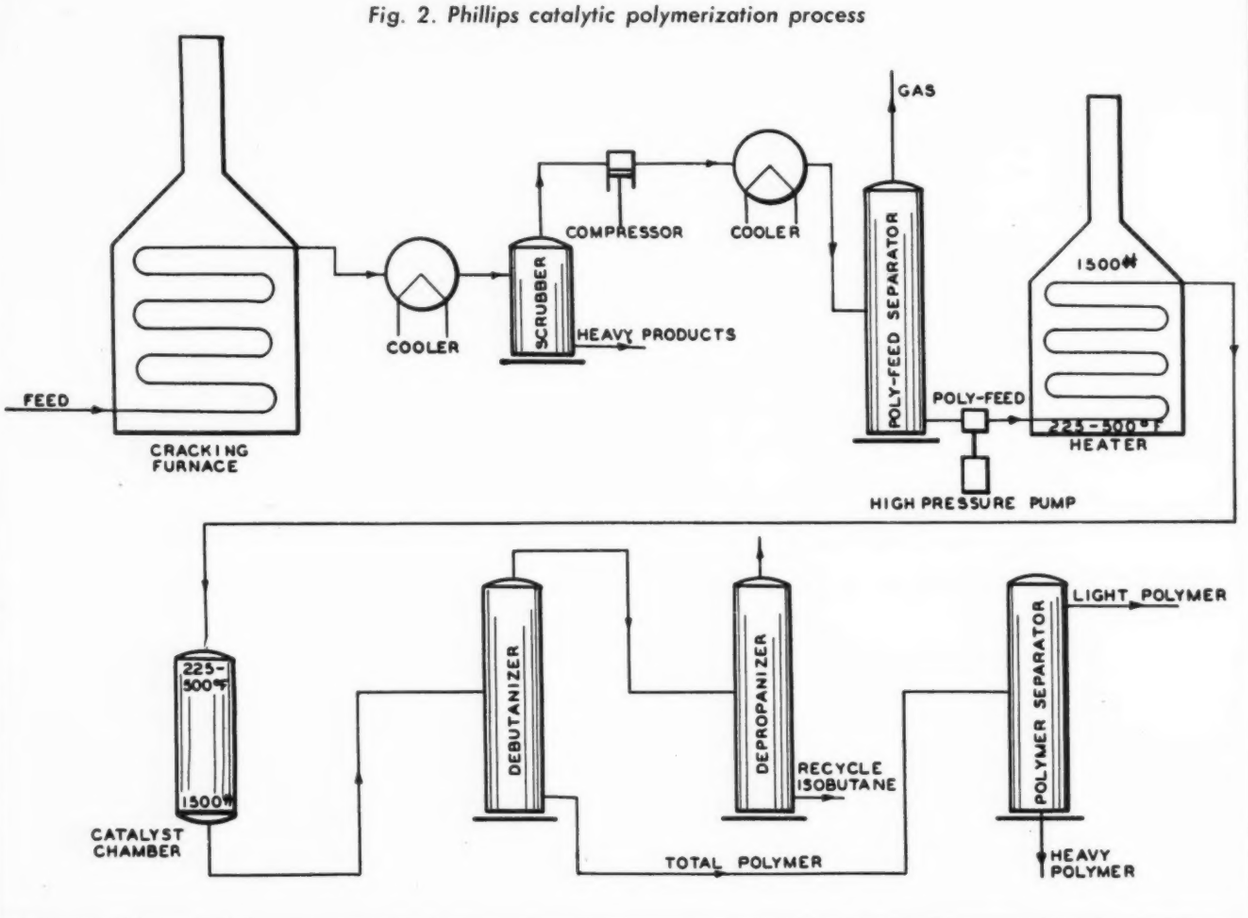
The *iso*butane cracker is simple in design and operation, and requires a relatively small amount of critical materials for its construction.

For most efficient operation, the *iso*butane used for olefin production should be pure. However, the presence of normal butane and lighter hydrocarbons in an aggregate amount of the order of 10 percent or less will not seriously affect the cracking operation.

Normal butane is the hydrocarbon most likely to occur as an impurity. Since normal butane is somewhat less stable than *iso*butane, it is decomposed to a greater extent than *iso*butane in a given time at a fixed temperature. The decomposition products of normal butane are principally hydrogen, methane, ethylene, and propylene. Only about 12 percent of the normal butane cracked reacts to form normal butylenes. In most present applications, butylenes are more useful than propylene or ethylene. Consequently, normal butane should be kept at as low a concentration as possible.

Propane cracks to form principally propylene, ethylene, methane, and hydrogen. It is much less reactive than the butanes, and acts substantially as a diluent when present in small amounts in *iso*butane being cracked. Since ethane and methane are even less reactive than propane, they, also, may be considered as diluents of the *iso*butane if they are

Fig. 2. Phillips catalytic polymerization process



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present in small amounts. The principal objection to propane, ethane, and methane as impurities in cracker feed *iso*butane is that they increase the size of the cracking and separation equipment without yielding compensating amounts of useful products.

Pentanes plus heavier compounds should not be permitted in the cracker feed *iso*butane in a concentration greater than one or two percent. These heavier compounds crack much more readily than butane and lighter hydrocarbons, and some of their decomposition products tend to degrade rapidly into tars and coke.

Olefins in the cracker feed *iso*butane will crack to yield olefins of lower molecular weight and other products. They will also polymerize thermally, but this reaction is affected by the concentration of the olefins. Butylenes may be present in the *iso*butane to the extent of about two percent without noticeably increasing the coke and tar formation. Propylene and ethylene can be tolerated in somewhat larger percentage because of their greater stability.

If sulphur compounds are present in the cracker feed *iso*butane they will crack and undergo other reactions similar to those of hydrocarbons. Sulphur will consequently be found in the olefinic products. Since most applications of *iso*butylene and propylene require them to be substantially free of sulphur compounds, it will usually be found desirable to free *iso*butane of sulphur compounds before using it for cracking stock.

Table 1 shows typical feed and product compositions for the *iso*butane cracker, when operating in conjunction with a polymerization (or codimer) unit. The composition of the product C_3 and C_4 is suitable for charging to a polymerization (or codimer) unit as shown in Fig. 1 and in some detail in Fig. 2. With uncracked *iso*butane added the product C_3 and C_4 is ideal as a feed stock to an alkylation unit as shown in Fig. 1.

It is of importance to consider the post war possibilities of going the extreme route on the flow diagram shown in Fig. 1 where isomerization, *iso*butane cracking, and alkylation are put into practice, assuming that butanes extraction has been raised to well above 90 percent and all the butanes are processed to produce alkylate. Under these circumstances it is estimated that the blend of butane-free natural gasoline and alkylate would have a Reid vapor pressure well under 10 lb. and an ASTM octane number unleaded of about 80. If in the course of developing the full war time potential of the situation, facilities were installed for the segregation of normal and *iso*pentane, means would be at hand for controlling vapor pressure and antiknock characteristics over a considerable range. It is therefore evident that these newer operations provide a means either now or in the future for the natural gasoline manufacturer to become a motor fuel manufacturer.

There are, of course, many other process possibilities for the natural gasoline hydrocarbons. The writer has presented the most simple ones partly to simplify the matter but more importantly because the things here discussed are almost entirely covered in pre-Pearl Harbor literature and in issued patents. Nevertheless, the comparatively simple processes described here serve to illustrate the new importance of normal butane.

It should be stated that there is not an easy road to the war time installation of such process steps in natural gasoline situations. Of paramount importance to the war effort is the accomplishment of the necessary results with the minimum expenditure of critical materials, transportation, time and manpower. Basically the problem is to find adequate supplies of *iso*butane and olefins to manufacture the required quantities of alkylate. Olefins can often be made in increased quantities by revising refinery operations. Normal butane for isomerization is abundantly available at refineries. Where conversion facilities already exist there are many possibilities of raising production by the elimination of bottlenecks. All of these things must be taken into account before "ground-up" proposals can receive serious consideration.

On the other hand, the writer has seen each successive estimate of the requirements for aviation gasoline higher than its predecessor. There has been no recession. It is probable that as long as the war lasts the requirements will continue to increase. To be forehanded, natural gasoline manufacturers should be developing projects for consideration by government agencies. In the meantime no greater service to the war effort can be performed than to take every step to increase deliveries of normal butane and *iso*butane as relatively pure materials or as mixed butanes or in natural gasoline to refineries that have facilities for converting these materials to 100-octane gasoline or to synthetic rubber.

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TABLE 1

***Iso*butane cracking operating conditions and products**
(Furnace with two parallel coils)

Total *iso*butane feed (gal. per day)	123,000
Pressure at inlet (lb. per sq. in. ga.)	97
Pressure at outlet (lb. per sq. in. ga.)	26
Temperatures °F.	
Furnace inlet (after heat exchange)	600
Outlet of convection sections	890
Outlet of radiant sections	1,350
Feed compositions, wt. percent	
C_3H_6 and lighter	1.11
C_3H_8	1.33
iC_4H_8 (+ nC_4H_8)	1.28
iC_4H_{10} (+ nC_4H_{10})	95.74
C_5+	0.54
	100.00
Product composition, wt. percent	
H_2	0.40
CH_4	4.64
C_2	0.95
C_3H_6	8.57
C_3H_8	1.83
iC_4H_8 (+ nC_4H_8)	13.83
iC_4H_{10} (+ nC_4H_{10})	68.61
C_5	1.17
	100.00
Percent *iso*butane cracked per pass	28
Ultimate yields	
Lb. iC_4H_8 per 100 lb. C_4 feed	49
Lb. C_3H_6 (net) per 100 lb. C_4 feed	26
Total useful products per 100 lb. C_4 feed	75

Increasing *Iso*butane Production in Natural Gasoline Plants*

By G. N. HILE, *Technical Supervisor,*
Natural Gasoline Department, Standard Oil Company of California

IT IS frequently said that the present international situation places American industry on the firing line. In the case of the natural gasoline industry, the objective has been very clearly indicated: Recover maximum additional *iso*butane with a minimum use of additional steel. To accomplish this, the principal points of attack open to the plant operator are the absorption system, the plant vapor cycle, and the rectification process. It is the purpose of this paper to review technical data available for the solution of this problem and to point out a few of the things that have already been done.

The absorption system is, of course, of prime importance in the extraction of *iso*butane. Through the use of the familiar Kremser formula[1], we are well equipped with the fundamental tools to handle this phase of the problem. The Kremser formula may be written in terms of readily available operating data as follows:

$$A = C_o \times \frac{O}{V} \times \frac{P}{cp}$$

Where:

A = Absorption factor,

C_o = Absorption oil constant

$$= 3.156 \times 1440 \times \frac{\text{Density}}{\text{Mol. weight}}$$

O = Absorption oil circulation, gal. per min.,

V = Gas to absorber, M. cu. ft. per day,

P = Absorber pressure, lb. abs.,

c = Factor to convert vapor pressure to fugacity,[2]

p = Vapor pressure of the pure hydrocarbon at absorber base temperature.

p = Vapor pressure of the pure hydrocarbon at absorber base temperature.

In order to translate this formula directly into terms of actual percent extraction, it is necessary to know the plate efficiency of the absorber and how to apply operating data. There is a considerable difference of opinion regarding exactly what data should be used in applying this formula. Unanswered questions are: Where should the temperature and pressure be taken, and should gas and oil measurements be made at the top or bottom of the absorber? These questions are the subject of current research study, and it is hoped we may expect an early answer. In the meantime, however, by arbitrarily selecting convenient points for taking the necessary data and correlating factors calculated from these data against the results of actual fractional analyses, it is possible to set up experimental curves that will permit full use of the formula with confidence. Fig. 1 presents such a correlation. Curves are also presented (Fig. 2 and Fig. 3), which permit the ready determination of the oil constant (C_o) and the vapor pressure correction factor (c), which are required for the solution of the absorption factor formula.

By the application of this formula and correlation, the solution of absorption problems becomes one of straightforward mathematics. The use of these data is not, however, recommended for vapor reabsorber calculations when unusual volume and temperature changes occur both in respect to the absorption oil and in respect to the gas.

In working out the economics of contemplated changes to improve absorption factors by refrigeration, increased oil circulation, changes in pressure, or changes in oil quality, particular care must be given to the operating position on the absorption factor curves. It will be noted that the advantages to be gained are approximately proportional to increases in absorption factor up to about 90 percent extraction. Beyond this point, the curves flatten out and increased absorption becomes more difficult.

After absorption, the method of handling plant vapors is of utmost importance. The method or combination of methods that will be most effective depends upon the operating pressure of the plant, available equipment, and plant capacity. For this reason, every plant becomes an individual problem. When there is ample oil circulating capacity, plant vapors may be satisfactorily treated in a separate absorber, a reabsorber, or by recycle to the plant intake. This system alone has limited application as vapor loads become abnormally high, at the high absorption factors required, the distillation system must operate at a relatively high pressure, and vapor cooling must be good. This method of operation is further limited to those cases where all *iso*butane can be retained in the plant product at relatively low pressures, around 25 lb. Reid. When Reid vapor pressures for total *iso*butane retention run from 30 to 40 lb., the reabsorber system cannot be expected to be effective.

When oil circulating capacities are limited and compressors are available, vapors may be more advantageously handled by compression, followed by cooling and recycle absorption. The pressure at which a vapor recompressor cycle is most effective again depends to

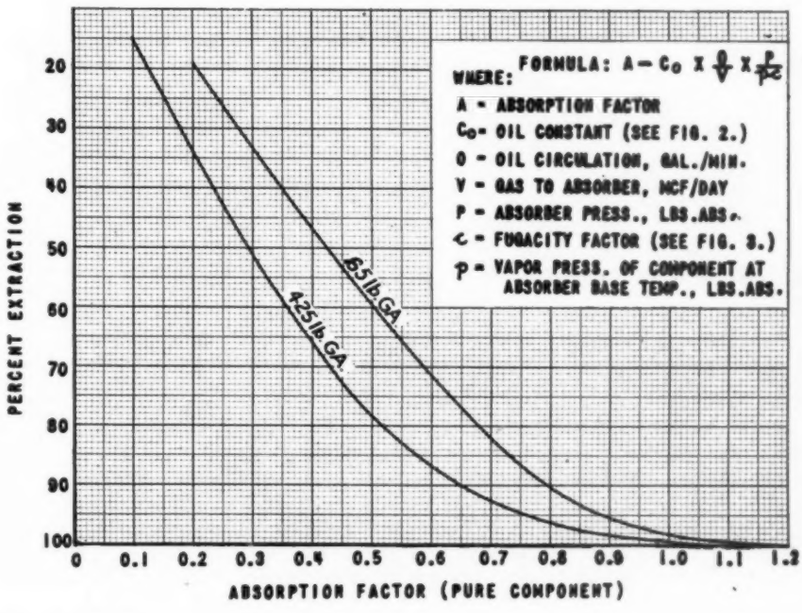
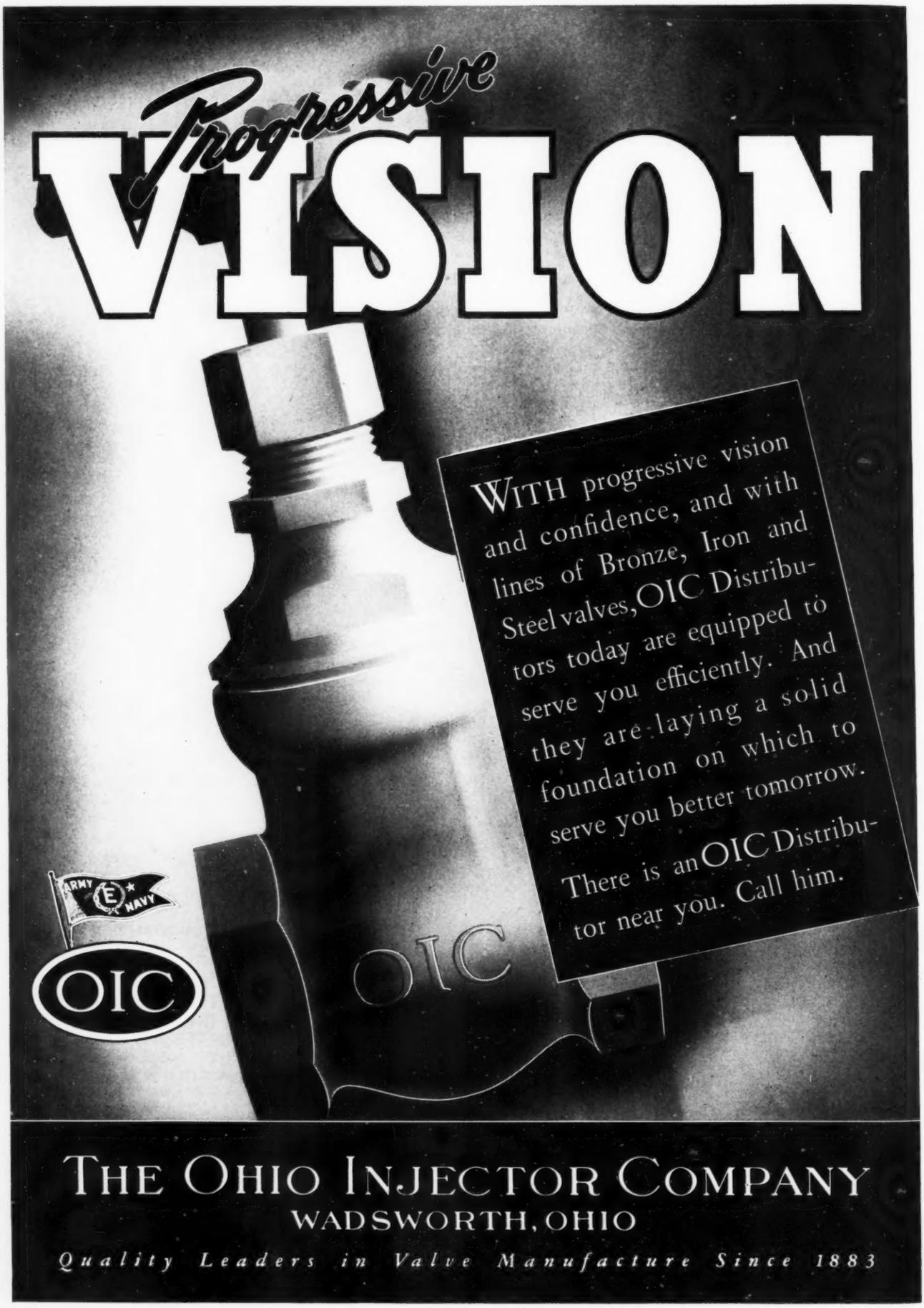


Fig. 1. Absorption factor vs. extraction for 16-plate absorbers

*Presented before California Natural Gasoline Association, September, 1942.

[1]"Theoretical Analysis the Key to Absorption Plant Design," by Alois Kremser, *Proceedings, California Natural Gasoline Association,* February, 1930.

[2]"Equilibrium Relations for Paraffin Hydrocarbons at High Pressures and Ordinary Temperatures," by Robert B. Bowman. *Proceedings, California Natural Gasoline Association,* May, 1938.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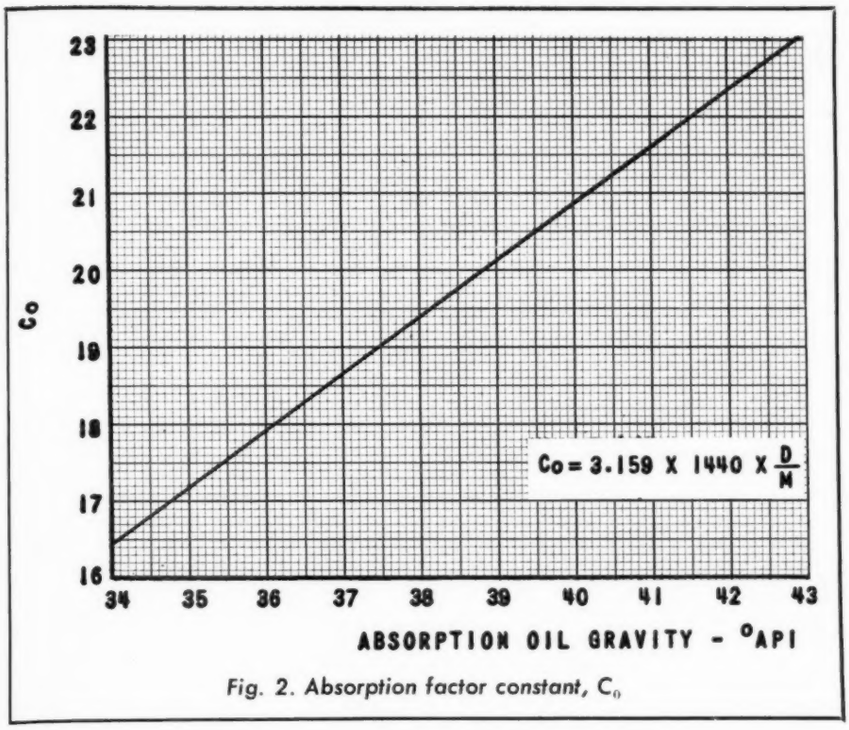

Fig. 2. Absorption factor constant, C_0

a large extent upon available oil capacity, available compressor capacity, and cooling conditions.

The capabilities of the vapor recompressor cycle to retain the *iso*butane absorbed are best illustrated by cycle calculations. Table 1 presents results of a series of such calculations wherein it is assumed that the oil capacity of a hypothetical plant is fixed at 350 gal. per min. Other assumed conditions are:

Field gas ..... 10,000 M. cu. ft. per day
Analysis of field gas:

	84.37%	G/M
Ethane	7.58	
Propane	4.01	
*Iso*butane	0.77	0.25
N-butane	1.49	0.469
*Iso*pentane (+)	1.78	0.71
Base stock (Reid V.P.) 9.4 lb.		

Absorber pressure ..... 65 lb. per sq. in.
Maximum oil circulation ..... 350 gal. per min.
Gravity of absorption oil ..... 36.8°A.P.I.
Stripper coil pressure ..... 20 lb. ga.
Temperature of stripper coils ..... 80°F.
Temperature of vapor recompressor coils ..... 80°F.

This plant, operating with a 65-lb. recompressor, will have a recycle to the absorber intake of 1855 gal. of *iso*butane and will retain 79.2 percent of the *iso*butane in the field gas. With a 125-lb. recompressor, the *iso*butane recycled to the absorber drops to 747 gal. and the plant will recover 86.1 percent of the *iso*butane. With a 250-lb. recompressor, the *iso*butane recycle is 260 gal. and the retention factor 89.0 percent. If it were possible to handle plant vapors without recycle, the *iso*butane retention factor would be 91.0 percent.

Table 1 also shows the recompressor indicated horsepower required for each pressure considered. For the assumed plant conditions, an increase in recompressor pressure from 65-lb. gauge to 125-lb. gauge resulted in an increase in *iso*butane production of 170 gal. per day, at a cost of 17 indicated hp. The step from 125-lb. gauge to 250-lb. gauge increased production 75 gal. per day at a cost of 25 indicated hp. A very definite decrease in returns is therefore indicated for the higher pressures, with the ultimate limit being fixed very largely by available equipment. In fixing this ultimate limit, rectifier capacity must be given consideration as high recompressor pressures result in a material increase in the volume of propane and fixed gases in rectifier feeds. These comparisons, although calculated for a specific plant, will be found quite typical, as the character of plant vapors is surprisingly uniform from plant to plant.

The matter of recycle to absorbers and fixed gas contents of rectifier feeds becomes of major importance in high pressure plant operations. Under such conditions, a direct vapor rectifier is proving a very advantageous cycle. Fig. 4 shows the flow sheet of such an installation in a Kettleman Hills plant. This cycle consists of directing the flow of all plant vapors, except cold oil vent tank vapors, through three stages of compression to a direct gas rectifier operating at such pressure that a propane-ethane reflux can be made in the presence of the fixed gases occurring in plant vapors. Vapors are cooled after the first and second stages of compression, but vapors from the final stage are delivered directly to the rectifier without cooling. All recompressor condensates are also directed through the vapor rectifier. This unit, operating with an overhead reflux ratio of two to one, is capable of reducing the ethane content of the kettle product to less than 1 percent and the propane content to 15-20 percent. The residue gas contains from a trace to one-half of one percent of *iso*butane.

This cycle eliminates all vapor recycle to absorber intake except that from the cold oil vent tank; it eliminates the fixed gas load from the final rectifier, and materially relieves the cooling requirements of the plant. This latter feature is particularly attractive, as plants "hopped up" for maximum *iso*butane absorption often are faced with overloaded cooling systems that are difficult to expand. It is, of course, desirable that oil and gas flows to the absorber be cooled to as low a temperature as practical. With the vapor rectifier cycle, however, vapors from the stripper, hot oil vent tank, and recompressor need be cooled only enough to accommodate compressor operation. With the vapor rectifier operating at 430 lb., a propane-ethane reflux can be

TABLE I

Cycle	Vapors to recompressor		Vapors to absorber		Absorption factor	Percent isobutane retained	Isobutane recovered gal. per day
	Recompressor, M. cu. ft. per day	Indicated horsepower	M. cu. ft. per day	G/M isobutane			
65 lb. ga. recompressor to absorber intake	814	51	534	3.47	0.776	79.2	1980
125 lb. ga. recompressor to absorber intake	696	68	338	2.31	0.791	86.1	2150
250 lb. ga. recompressor to absorber intake	677	93	215	1.21	0.800	89.0	2225
*With no recycle to absorber	.....	..	.....	.....	0.817	91.0	2275

*Presuming all isobutane absorbed can be retained without recycle.

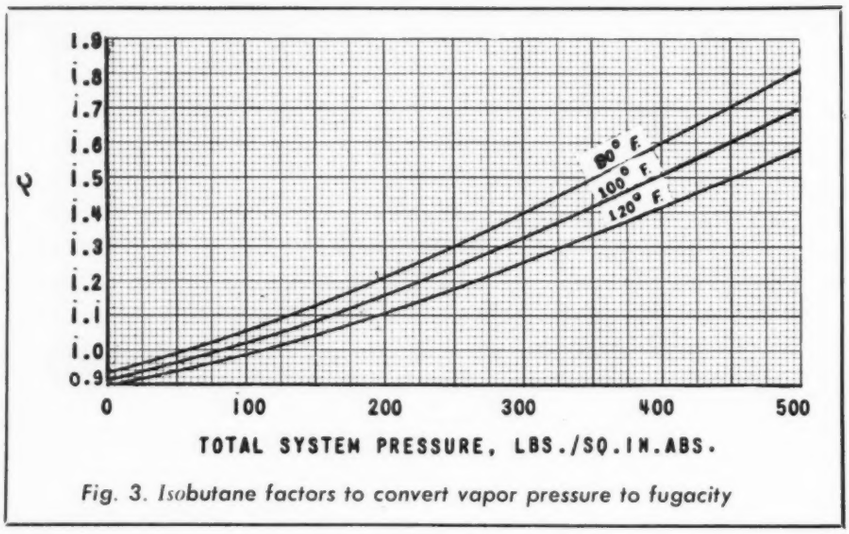

Fig. 3. Isobutane factors to convert vapor pressure to fugacity

made at temperatures around 100° F. The condensation of a propane reflux for final gasoline rectification is also greatly facilitated because of the complete elimination of methane and substantially complete removal of ethane from the rectifier feed.

To gain the maximum advantage of existing equipment, consideration must also be given to the method of venting rich oil. In plants operating at 150 lb. and above, a very considerable advantage can be gained by venting the rich oil from the absorber before it enters the heat exchanger. This cold oil vent should be taken at as low a pressure as is practical. Vapors vented here will usually contain less than 0.5 G/M *iso*butane and the bulk of the fixed gas. This vapor can therefore be recycled to the absorber intake or treated separately with very little loss, and vapors occurring down stream from this point are much more condensable. The advantage of such a cold oil vent tank in plants operating at pressures below 150 lb. is questionable, as gain that can be realized is offset by the necessity for using rich oil pumps.

The advisibility of venting rich oil at points between the cold oil vent tank and the stripper is questionable. With a recompressor cycle there is no advantage to be gained from a condensation standpoint as poorer condensation in the stripper coils is offset by better condensation in the vapor recompressor system. There is, however, a horsepower and stripper capacity advantage to be gained by venting the rich oil before it enters the preheaters. Vapors vented here contain in the order of 2.0 G/M *iso*butane, and their recycle direct to the absorber is to be avoided where there is insufficient absorption oil circulating capacity to maintain high absorption factors.

The operation and instrumentation of rectifier systems for total *iso*butane recovery are subjects too broad to be covered extensively herein. A few generalizations will serve to outline the problems, however. Two methods are in common use: One, wherein all *iso*butane is retained in the natural gasoline, which is then delivered to refineries for further fractionation, and the other, which effects separation of *iso*butane at the gasoline plant either as such or as a fraction of liquefied petroleum gas.

The retention of *iso*butane in the natural gasoline is contingent upon the ability to make a propane reflux for the gasoline rectifier. The control of such a system is most satisfactorily effected by placing the control element of the kettle vaporizer in the column 5 or 6 plates above the feed. This instrumentation results in variation of kettle and top temperatures in phase with the quality of the feed, and at the same time prevents the loss of *iso*butane in the residue vapor.

The production of *iso*butane as such or in a liquefied petroleum gas cut lends itself to a large variety of equipment arrangements and instrumentation. The arrangement most effective will be dictated by available equipment and specification requirements. Under certain conditions, rectifier side-cuts may be taken off which contain the bulk of the *iso*butane. When using a vapor rectifier, the *iso*butane may be isolated by cutting deep into the natural gasoline and condensing the entire rectifier residue for an *iso*butane cut. When *iso*butane is produced as such, series rectification becomes necessary.

In conclusion, it is important to emphasize again that the most satisfactory method of producing the maximum production of *iso*butane with the minimum use of steel is an individual problem for each plant. With regard to absorption of *iso*butane, the absorption factor formula and correlation are available that permit a mathematical solution to this phase of the problem.

The handling of plant vapors presents no problem when adequate absorption oil capacity is available. With oil capacity limited, recompressor or vapor rectifier systems offer the most promising solution.

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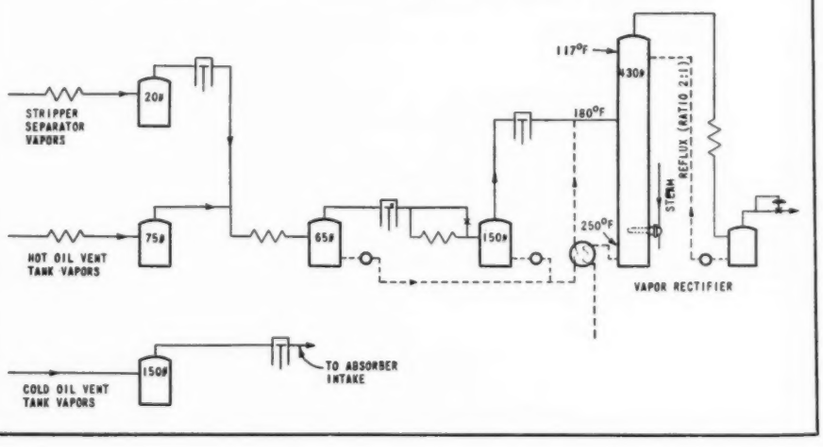
Fig. 4. Direct vapor rectifier cycle for handling plant vapors



Viscosity of Propane, Butane, and *Iso*butane*

By M. R. LIPKIN, J. A. DAVISON‡, and S. S. KURTZ, JR.

Sun Oil Company

FEW data are available in the literature on the viscosity of the liquid hydrocarbons of less than five carbon atoms. Reviews by Evans[4] and International Critical Tables[8] list only data by Kuenen and Visser on liquid *n*-butane at temperatures ranging from approximately —20° to +100°F. Sage and co-workers[11,14] determined viscosities of liquid *n*- and *iso*butane and liquid propane at temperatures above 100°F. The authors have determined the kinematic viscosity of liquid propane from —105° to +70°F., of *n*-butane from —105° to +100°F. and of *iso*butane from —105° to +48°F. The viscosities were determined with an accuracy of ±2 percent in two types of specially designed capillary-flow viscometers, one for the higher temperature range (Fig. 1), and the other for the lower (Fig. 2). Only a brief description of the two viscometers will be given because an improved viscometer is in the process of development.

Apparatus and Method

The first viscometer (Fig. 1) was made from the stem of a high-distillation thermometer (30-760°F.), whose ends were ground to a sharp edge bisecting the capillary. The sharp ends do not allow liquid to remain on top of the capillary and, therefore, assure a clean upper meniscus. Without this precaution a chain of bubbles is formed above the top meniscus because liquid is sucked into the capillary. The thermometer stem is held in a glass tube with a cap carrying a Hoke needle valve clamped over its open end. This tube is 28 cm. (11 in.) long, 14 mm. (0.51 in.) O.D., and 10 mm. (0.39 in.) I.D., and will withstand an internal pressure of 140 lb. per sq. in. The viscometer assembly is filled to mark A, and bulbs a and b fill by gravity. After coming to temperature, the viscometer assembly is inverted and the time of flow measured between marks B and A. As the measurement is dependent on the ratio of surface tension to density,

$$\left.\begin{array}{l}\text{Percent error due to difference between}\\ \text{surface tension of calibrating liquid}\\ \text{and unknown}\end{array}\right\} = \frac{0.204}{H}\left(\frac{1}{r_1}-\frac{1}{r_2}\right)\left(\frac{\gamma_1}{d_1}-\frac{\gamma_2}{d_2}\right)$$

where:

H = head, cm.,
r_1, r_2 = radii at liquid levels, cm.,
γ_1, γ_2 = surface tensions, and
d_1, d_2 = densities

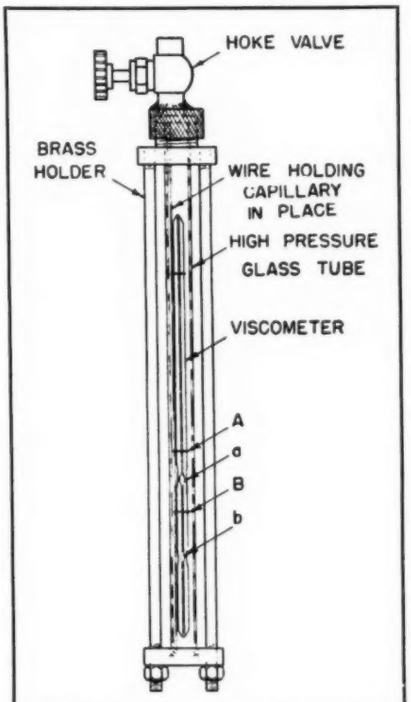


Fig. 1. High-pressure viscometer

the viscometer was calibrated with liquids (benzene, ethyl alcohol, acetone) whose ratios of surface tension to density are fairly close to those of the lower boiling hydrocarbons. Viscosities were run with this instrument in baths thermostated within ±0.1°F.

This viscometer cannot be conveniently used at temperatures below 32°F. but is suitable for higher temperatures and high pressures; it is limited only by the strength of the containing tube. (When working with high pressure in this viscometer, a face mask should be used and the arms protected.)

The viscometer used at the lower temperatures and pressures was a modified Fenske type (Fig. 2). This viscometer is simple to use and is limited to a gauge pressure of about 3 atmospheres because of leakage at the stopcocks. The viscometer is filled through valve A. Viscosities are always run with stopcocks A and B closed to the atmosphere, and with the vapor passage open through the bridge between A and B. After the viscometer has been charged and has come to temperature, the calibrated bulb C is filled by one of two procedures. When the vapor pressure is below atmospheric pressure, A and B are opened to the atmosphere with the bridge closed, and pressure is applied to A. At vapor pressures higher than atmospheric, the bridge and A are closed and B is cautiously opened so that the pressure on side A forces the liquid slowly up side B. After each run the liquid level on scale D is read. The viscometer constant is obtained from a calibration curve of liquid level of scale D vs. calibration constant.

For the temperature control below 32°F., a large silvered Dewar flask with two visible strips was used. The bath was filled with acetone cooled by solid carbon dioxide, and was provided with an air-driven stirrer. A calibrated single-junction copper-constantan thermocouple and a Charles Engelhard type P. I. millivoltmeter were used for temperature measurement. The temperature could be controlled within 1°F. by adding shavings of solid carbon dioxide. When cooled to —70°F., this bath would not rise in temperature more than 2°F. in 60 minutes.

The hydrocarbons on which data were obtained were commercial products of the Ohio Chemical and Manufacturing Company. Purity as determined in our laboratory was 99+ percent; the purities stated in their catalog are propane 99.9 percent, *n*-butane 99, *iso*butane 99.

Results

The kinematic viscosities over a temperature range were determined on propane, *n*-butane and *iso*butane (Fig. 3). The data form good straight lines when plotted on A.S.T.M. chart D-341-37T, which has been modified by dividing the viscosity scale by 10 and subtracting 100°F. from the temperature scale. Ten centistokes on the original graph equal one centistoke on the revised graph, and 0°F. on the original graph equals —100°F. on the revised graph. No single determination deviates more than 4 percent from its line. Viscosities determined on propane and *n*-butane at the lower temperatures and pressures in the modified Fenske viscometer are in excellent alignment with the viscosities determined in the other instrument at the higher temperatures and pressures. Data from International Critical Tables on *n*-butane, determined in 1913 by Kuenen and Visser,[8] fall on our curve. Sage and Lacey[11,14] gave a value 2 percent lower than our best value for *n*-butane and

*Published by *Industrial and Engineering Chemistry*, August, 1942.

‡Present address, University of Pennsylvania, Philadelphia.

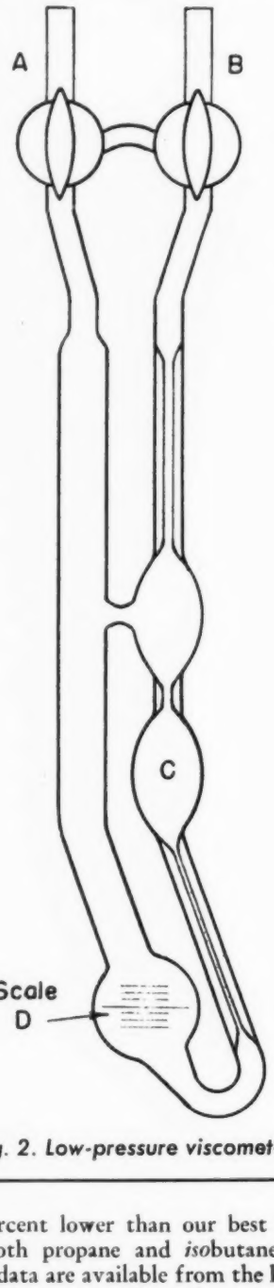


Fig. 2. Low-pressure viscometer

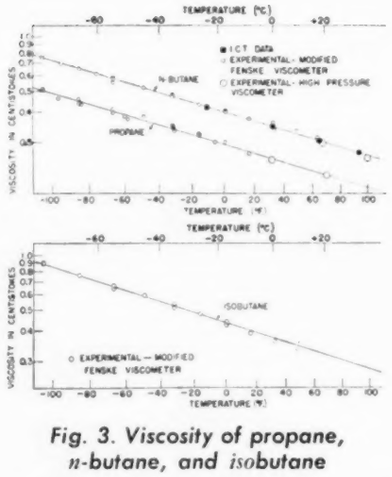


Fig. 3. Viscosity of propane, *n*-butane, and *iso*butane

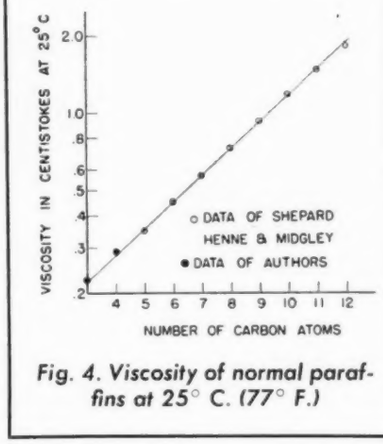


Fig. 4. Viscosity of normal paraffins at 25° C. (77° F.)

12 percent lower than our best value for both propane and *iso*butane. No other data are available from the literature. However, a plot (Fig. 4) of log kinematic viscosity at 25°C. vs. number of carbon atoms for the normal liquid hydrocarbons, using data of Shepard, Henne, and Midgley,[15] gives a straight line with which our experimental data for propane and *n*-butane agree with +2 and +4 percent, respectively. Similar type plots by Wiggins[16] of log absolute viscosity at 20°C. vs. number of carbon atoms, and by Nissan and Dunstan[10] of log absolute viscosity vs. molecular volume and log molecular volume, give similar agreement with our data.

For engineering purposes, absolute viscosity is often desired rather than kinematic viscosity. Table 1 gives the kinematic viscosity, density, and absolute viscosity at 20°F. intervals from —100° to +100°F. for the three hydrocarbons. The kinematic viscosities were read from Fig. 3 and are accurate within ±2 percent. The densities are best values obtained after a search of the literature[1,2,3,5,6,7,9-12] and are dependable within ±0.001. The absolute viscosity is calculated from these data and is also accurate within ±2 percent.

Acknowledgment

The authors wish to acknowledge the assistance of W. T. Harvey and I. W. Mills in connection with a portion of this work.

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TABLE I

Viscosity and density of propane, *n*-butane and *iso*butane*

Temp.		Propane			n-Butane			Isobutane		
°C.	°F.	*d t/4 (3, 5, 9, 12)*	Centistokes	Centipoises	*d t/4 (2, 3, 6, 7, 13)*	Centistokes	Centipoises	*d t/4 (1, 2, 3, 11)*	Centistokes	Centipoises
−73.3	−100	0.618	0.48^{7}	0.30^{1}	0.674	0.72^{0}	0.48^{5}	0.661	0.85^{0}	0.56^{2}
−62.2	− 80	0.606	0.43^{2}	0.26^{2}	0.664	0.62^{5}	0.41^{5}	0.649	0.72^{5}	0.47^{1}
−51.1	− 60	0.593	0.39^{0}	0.23^{1}	0.653	0.55^{3}	0.36^{1}	0.638	0.62^{5}	0.39^{9}
−40.0	− 40	0.580	0.35^{3}	0.20^{5}	0.642	0.49^{0}	0.31^{5}	0.626	0.55^{0}	0.34^{4}
−28.9	− 20	0.567	0.32^{2}	0.18^{3}	0.631	0.44^{0}	0.27^{8}	0.614	0.48^{5}	0.29^{8}
−17.8	0	0.553	0.29^{5}	0.16^{2}	0.619	0.40^{0}	0.24^{8}	0.602	0.43^{3}	0.26^{1}
− 6.7	20	0.539	0.27^{3}	0.14^{7}	0.608	0.36^{4}	0.22^{1}	0.589	0.39^{2}	0.23^{1}
+ 4.4	40	0.525	0.25^{4}	0.13^{3}	0.596	0.33^{5}	0.20^{0}	0.577	0.35^{6}	0.20^{5}
+15.6	60	0.509	0.23^{7}	0.12^{1}	0.584	0.31^{0}	0.18^{1}	0.564	(0.32^{7})	(0.18^{4})
+26.7	80	0.492	(0.22^{4})	(0.11^{0})	0.571	0.28^{8}	0.16^{4}	0.551	(0.30^{0})	(0.16^{5})
+37.8	100	0.474	(0.21^{0})	(0.10^{0})	0.558	0.26^{8}	0.15^{0}	0.537	(0.27^{8})	(0.14^{9})

*Values in parentheses obtained by extrapolation.

In WAR or PEACE its Vogt for better HEAT TRANSFER EQUIPMENT

1. Heat Exchangers in the foreground have monel metal shells, admiralty metal tubes and naval bronze tube sheets, floating head covers, and baffles. Vogt Ell Bolts are used on floating head covers.
2. Reactors for catalytic polymerization units being assembled and tested. Each is of welded construction and has bolted-on hinged covers.
3. Group of Diesel Oil Exchangers for a visbreaker. Used to exchange heat between diesel oil and corrosive crude containing salt and sulphur compounds.
4. 62″x30′-6″ long Gas Cooler for a catalytic unit in a large refinery. Tube bundle at right is for a second unit.

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A TYPE AND SIZE FOR EVERY PURPOSE

Phase Equilibria at High Temperatures*

By

ROBERT ROY WHITE and GEORGE GRANGER BROWN

University of Michigan

IN the production and refining of petroleum, the vaporization or condensation of hydrocarbon mixtures is involved in nearly every major operation. Recent developments in the high-temperature processing of petroleum have focused increased attention upon the importance of data on the vaporization of petroleum hydrocarbons in the temperature range from 500°F. upward. Not only are data in this temperature range almost nonexistent but also vaporization data on the hydrocarbons of greater molecular weight than heptane are exceedingly meager for any temperature and consist mostly of atmospheric vaporizations of various distillate oils[3, 13, 16, 18, 19].

Apparatus

The different methods used in the determination of vapor-liquid equilibria can be classified under two headings: static or batch operation, and continuous or flow operation. The flow method is preferable for studying the high-temperature vapor-liquid equilibria of hydrocarbons because the extent of decomposition or cracking can be reduced to a minimum by virtue of the limited time of exposure to high temperature and because the relatively large samples required for analysis can be easily obtained. The only serious disadvantage in a continuous flow system is the difficulty of reliable liquid level control in the vapor-liquid separator at high temperature and pressure.

Flow Diagram. Fig. 1 shows the flow diagram of the apparatus used in this work.

Oil is forced by the high-pressure pump, 1, through furnace 2 where the temperature is raised to the desired conditions, into separator 3 which is immersed in the constant-temperature molten salt bath, 4. The constant-temperature bath maintains a uniform temperature in the separator by eliminating radiation losses. Vapor is drawn from the top and liquid from the bottom of the separator and transferred to the coolers, 5, where the streams are cooled to room temperature. From the coolers the oil passes to atmospheric separators 6 and 7, where any noncondensable gases present may be separated from the cooled streams and collected in suitable receivers. During a run the entire liquid and condensed vapor streams are withdrawn as samples from these separators into suitable receivers. When no samples are being withdrawn, the liquids pass to recycle tank 8 where they are mixed and recirculated to the high-pressure pump by auxiliary pump 9.

The furnace may be operated under constant controlled pressure by means of the back-pressure valve, A. Separator pressure is controlled by valve C. The liquid level in the separator is maintained by valve B. Stream temperatures are measured by thermocouples V, X, Y, and Z. The salt bath temperature is measured by thermocouple W. Separator pressure is indicated by gauge P_1, furnace transfer pressure by gauge P_2, and furnace inlet pressure by gauge P_3. Line heaters (110-volt) are wound on the furnace transfer line to the separator and on the distillate line from the separator.

Separator. In an experimental study of vaporization equilibria, it is essential that no liquid phase be included in the vapor stream and that no vapor phase be included in the liquid stream from the separator.

The inclusion of liquid in the vapor stream may be avoided by the use of an adequate entrainment removal device. The inclusion of vapor in the liquid stream may be avoided by maintaining a liquid seal in the bottom of the separator. The separator and drawoff lines must be of the smallest feasible dimensions to reduce holdup of material and thereby to decrease the time it is exposed to the high temperatures.

Fig. 2 is a drawing of the assembled separator. Its operation is as follows: The feed, an intimate mixture of liquid and vapor in turbulent flow, enters the separator through the side wall 2, where it impinges directly upon the separator thermocouple well, T, and the side of a modified Hagen 1-in. mist separator, 5. Vapor and any entrained liquid sweep upward through the annulus between the Hagen separator and the body of the high-pressure separator into the vanes, 4, of the Hagen separator, where it is given a downward rotary motion. The entrained liquid, due to this rotary motion and the subsequently decreased velocity, is deposited upon the sides of the Hagen separator while the dry vapor continues upward and out through distillate line 6. The entrainment liquid drains through a sealed outlet, 7, to the bottom of the main separator.

Liquid from the feed mixture drains directly to a well 1 in. in diameter and 3 in. deep in the bottom of the separator. A liquid level is indicated and maintained in this well. The liquid then passes through the bottom drawoff line to the liquid coolers.

The separator, designed for operation at 1000°F. at 1000 lb. per sq. in. pressure, was machined from a forged-steel billet of the composition, carbon 0.12 percent, chromium 1.5, and molybdenum 0.5.

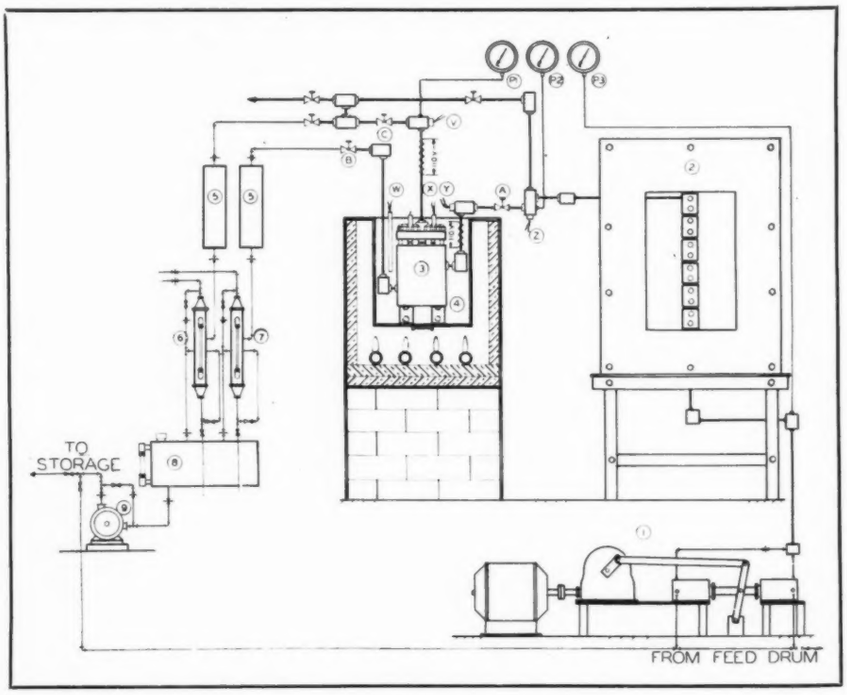


Fig. 1. Flow diagram of apparatus for vapor-liquid separation

Experimental liquid-vapor phase equilibrium data have been obtained for petroleum fractions boiling from 95° to 750° F. at temperatures from 300° to 820° F. and at pressures from 50 to 700 pounds per square inch. The results have been used to extend the estimated ideal equilibrium vaporization constants to hydrocarbons having boiling points up to 925° F. at temperatures from 0° to 1000° F. and at pressures from 1 atmosphere to 1000 pounds per square inch, and to develop a relation for estimating the values of the vaporization constants in the critical and retrograde regions of complex hydrocarbon mixtures.

*Presented before American Chemical Society, Buffalo, New York, September 10, 1942, and published in *Industrial and Engineering Chemistry*, October, 1942.

A creep strength of 9000 lb. per sq. in. and a safety factor of 3 were used in designing the wall thickness.[15]

Ten ¾-in. studs, made of high-carbon steel (1.00-1.50 percent chromium and 0.40-0.60 percent molybdenum), hold the flange. This steel was normalized at 1724°F. and drawn back to 1250°F. to obtain a creep strength of about 20,000 lb. per sq. in.

The flange is gasketed with an Armco iron ring between machined knife edges, as used with success by Huntington and Brown[6] under cracking conditions and in molten salt. The thermocouple well, which extends to the level of the feed intake, is sealed into the flange by means of a cone compression joint similar to those shown in Fig. 3. The single electrical lead necessary for the operation of the liquid level indicator passes through the flange by means of a soapstone seal.

The assembled separator was tested for strength and leakage to a hydraulic pressure of 10,000 lb. per sq. in., at room temperature.

Liquid Level Control

The maintenance of a liquid seal at high pressures at a substantially constant level in the 1- by 3-in. well presented a difficult problem. Contributing to the difficulty of operating a level indicator with such a small quantity of liquid was the expectancy of operation near critical conditions where the physical properties of the liquid and vapor phases approach one another. In this region the sensitivity of any type of indicator falls off rapidly as the critical point is approached.

After prolonged consideration of more apparent means, the use of a capacitance measurement as the basis of liquid level indication was adopted.

Accordingly, a vertical plate condenser was designed to fit the 1- by 3-in. well in the separator floor. This condenser is comprised of four cylinders machined from chromium-tungsten steel, 3 in. in length, 1/64 in. in wall thickness, and of diameters such that the annular space between the cylinders when mounted one inside another is 1/16 in. The cylinders are accurately spaced by being mounted on two pairs of glass posts set at right angles to one another (Fig. 2A). As shown, alternate rings are offset vertically ¼ in. and are connected electrically by a wire at the bottom which grounds one side of the condenser, and by a brass machine bolt at the top to which the insulated external lead to the other side is connected.

This condenser is placed in the bottom of the separator (Fig. 2); and when the condenser is connected to a high-frequency alternating circuit, liquid rising between the plates increases the capacitance.

The capacitance of the condenser is balanced against a control condenser in a capacitance bridge, one side of which is also grounded. The balance of the bridge is indicated by an oval image on the screen of a cathode-ray oscillograph for visual observation. Distortion of the image indicates unbalance of the bridge. A sweep circuit in the bridge gives direction to the image distortion and consequently to the unbalance of the bridge.

In operation the bomb is emptied of all liquid and the bridge balanced by an adjustment of the control condenser. The dial of this condenser is calibrated, and a reading is taken. The separator is then filled with liquid to above the level of the separator condenser and the bridge again brought into balance by adjustment of the control condenser, where the new position of the dial is recorded. The control condenser is then adjusted to some intermediate point (middle, high, or low) as desired in the separator well, and the bridge brought into balance by draining liquid from the separator. Liquid level is maintained

(*Continued on Page 286*)

Fig. 2. Equilibrium separator (dimensions in inches)

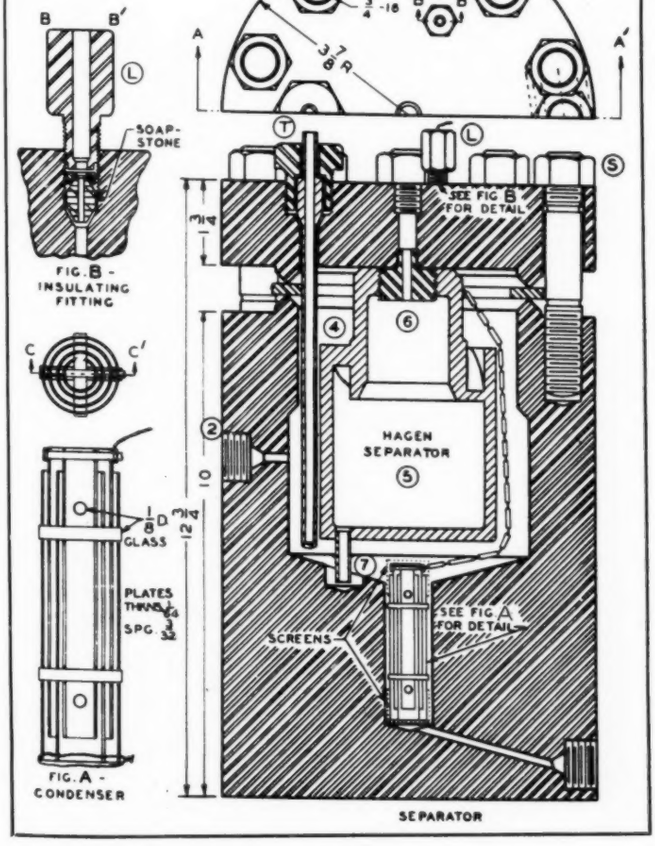
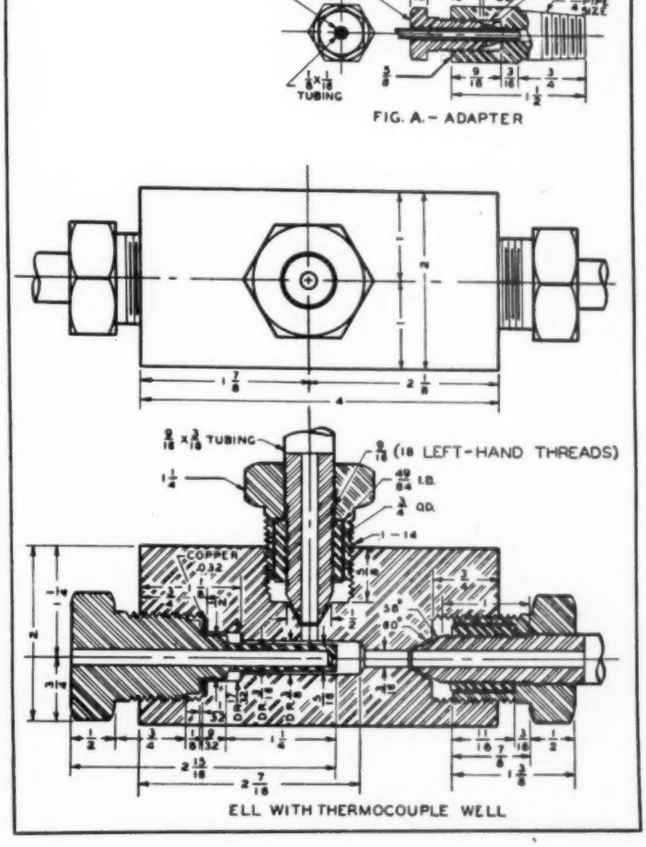


Fig. 3. Cone compression fittings (dimensions in inches)



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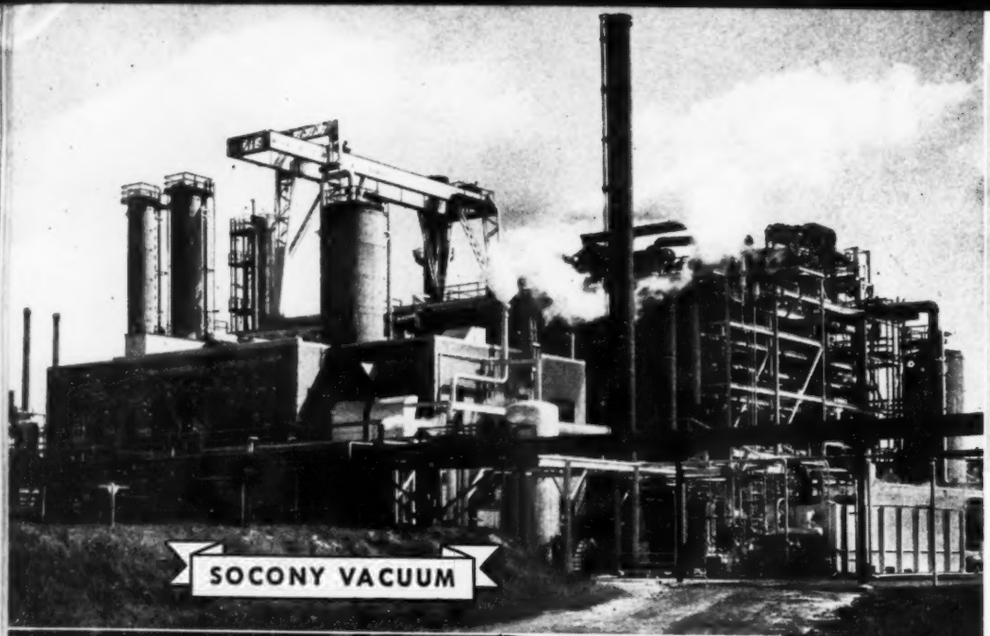

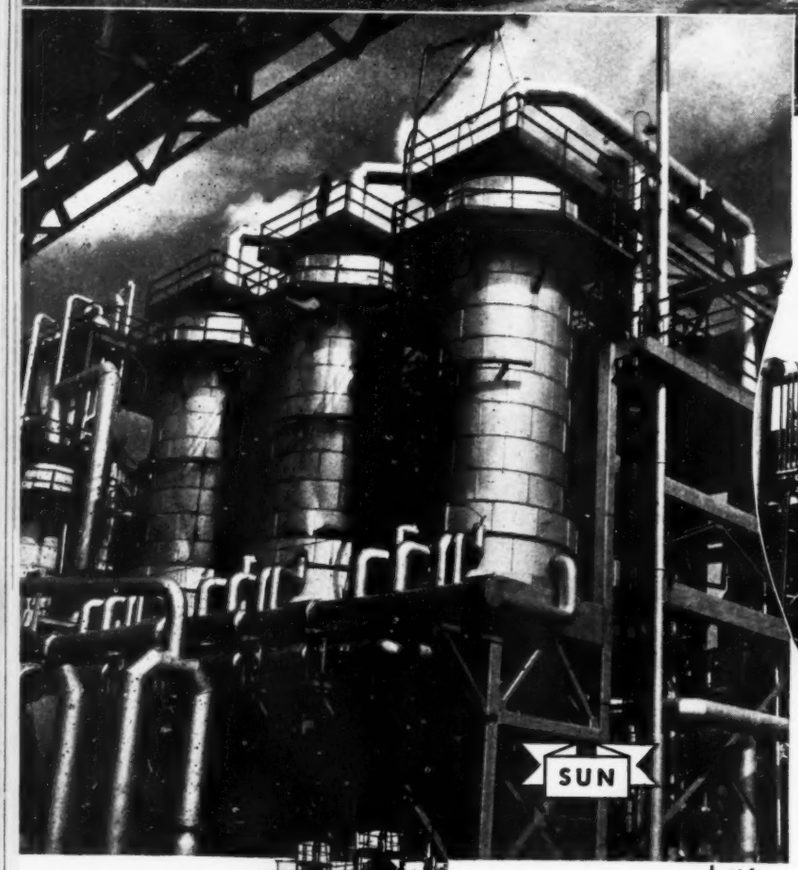

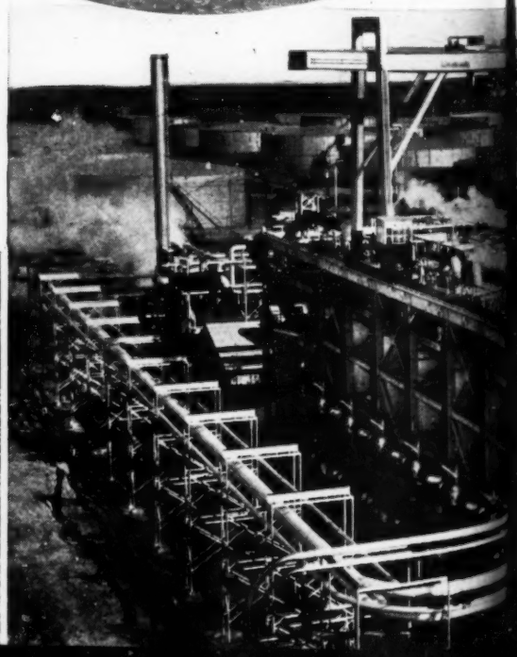

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TABLE 1

Composition of butane-and oil-free naphtha (gravity 82.9°A.P.I. at 60°F.)

	Volume, percent	Weight, percent	Mole, percent	Mol. weight
Pentanes	58.9	56.4	61.6	72
"Hexanes"	25.6	26.5	24.5	85.5*
"Heptanes"	15.5	17.1	13.9	97*
			Av.	78.7

*Experimentally determined.

TABLE 2

Podbielniak analytical distillation of domestic furnace oil No. 3 (gravity 40.6°A.P.I. at 60°F.)

Distn., °F.	Sample of Jan. 1, 1940	Sample of Mar. 7, 1940
Initial B. P.	182	180
10% over by bol.)	366	366
30%	466	464
50%	554	551
70%	608	609
90%	680	680
95%	713	713

TABLE 3

Molecular weight determination on distillate cuts

Sample No.	Boiling range, °F.	Volumetric Av. B. P., °F.	Molecular weight
1	300-378	339	134
2	375-444	409	165
3	501-556	528	212
4	556-601	578	231
5	626-666	646	271
6	666-750	708	306
7	375-444	409	159
8	556-601	578	229
9	625-675	650	267
10	300-750	525	207
11	541-401	472	186
12	300-325	312	132
13	350-375	362	148
14	500-527	514	210
15	598-628	613	260
16	628-648	638	267
17	674-700	687	279
18	700-750†	725	337
19	Heptanes	195	97
20	Hexanes	145	85.5
21*	636-686	661	267
22*	526-570	548	196
23*	317-378	347	143

†Residue.
*Distillate cut from the vapor sample of run 30 representing cracked material.

(*Continued from Page 283*)

by observing the distortion of the balance image and suitably adjusting the liquid drawoff.

This arrangement provides an exceedingly accurate and easy control at low pressures, and makes possible the maintenance of a liquid seal to reduced pressure conditions of 0.95 at the critical temperature. The directional characteristics of the image distortion when unbalanced, due to the sweep circuit, gives immediate indication as to whether the separator liquid level is high or low.

Constant-temperature bath. The salt mixture used is about 45 percent sodium nitrate and 55 percent potassium nitrate, and has a melting point of about 465°F. The tank is of low-carbon steel, 12 by 16 by 19 in., with walls ¼-in. thick and a bottom plate ½-in. thick, reinforced by a length of channel iron. All joints were welded inside and out. Angle-iron studs, welded to the bottom, support the separator.

TABLE 6. Experimental and analytical data on

Run No.[a]	Temperature, °F.	Pressure, Lb./Sq. In. Abs.	Sample Vol. at 60° F., Cc.	Sp. Gr. of Sample at 60° F.	Wt. of Analytical Sample, Grams	Cumulative Volume 86–95° F. (pentanes)	135–156° F. (hexanes)	175–209° F. (heptanes)	209–300° F.	300–350° F.	350–400° F.
1-L	662	684	1783.8	0.7619	152.2	41.5	62.0	76.3	79.5	85.2	95.4
1-V			395.8	0.7167	143.2	74.5	105.5	126.5	129.0	134.2	144.5
2-L	659	596	906.5	0.7672	152.8	40.5	61.2	73.7	76.0	83.0	94.7
2-V			394.9	0.7159	144.9	75.0	108.0	130.0	134.0	140.4	150.3
3-L	656	420	493.5	0.7967	157.5	22.5	35.0	44.7	46.5	50.8	61.2
3-V			617.5	0.7159	149.4	82.5	117.0	145.0	147.4	150.8	160.9
4-L	657	216	410.5	0.8223	163.7	9.5	15.5	20.0	21.6	25.7	33.3
4-V			1265.0	0.7268	144.8	67.5	95.5	114.5	117.9	124.8	135.7
5-L	663	503	618.7	0.7894	156.0	29.0	43.0	54.6	57.1	62.5	73.0
5-V			600.2	0.7232	141.1	77.0	110.0	131.2	135.0	141.7	152.2
6-L	682	596	599.6	0.7765	154.7	35.5	52.5	65.7	68.7	73.2	85.2
6-V			567.8	0.7231	143.3	71.5	102.0	119.8	123.7	129.3	139.9
7-L	699	595	439.0	0.7809	155.9	33.0	50.0	61.2	63.8	68.1	78.1
7-V			779.1	0.7304	144.9	67.0	96.5	114.0	117.1	122.0	134.2
8-L	700	650	409.6	0.7733	153.7	38.0	56.5	68.8	71.8	75.9	86.5
8-V			879.8	0.7298	144.7	63.5	90.8	108.3	112.3	116.7	126.7
9-L	700	501	392.7	0.7951	159.1	25 0	39.0	48.3	50.7	54.2	63.5
9-V			875.5	0.7269	145.9	68.5	99.0	115.6	119.0	124.5	135.0
10-L	700	344	355.1	0.8172	163 3	13.5	31.0	37.0	39.2	41.3	48.5
10-V			896.5	0.7343	145.9	64.5	93.5	110.0	113.7	118.4	129.4
11-L	575	498	1517.1	0.7617	151.8	44.0	65.5	79.3	82.6	86.9	98.6
11-V			393.5	0.6861	137.5	101.0	139.0	160.2	163.8	167.8	175.5
12-L	593	340	607.8	0.7917	157.5	24.0	38.0	48.4	51.0	54.7	66.7
12-V			493.9	0.6931	138.6	93.0	130.0	151.8	155.8	160.8	170.3
13-L	580	205	418.2	0.8118	160.7	12.5	21.2	26.2	28.6	32.0	41.7
13-V			595.4	0.7035	139.4	85.0	121.0	141.7	145.7	151.0	161.9
14-L	710	546	362.7	0.7902	157.2	27.5	42.5	52.5	55 2	59.2	69.1
14-V			914.7	0.7333	146.8	65.2	94.5	112.0	115.3	120.8	131.5
15-L	580	352	1054.5	0.7883	155.9	26.5	40.3	50.0	53.0	58.0	71.4
15-V			446.6	0.6924	138.4	97.0	133.5	153.6	157.4	162 7	173.5
16-L	583	147	528.6	0.8187	162.8	8.0	14.0	18.4	20.3	23.6	33.3
16-V			464.2	0.7142	141.7	75.7	107.6	126.7	130.8	137.7	153.3
17-L	660	517	1682.5	0.7829	155.0	32.5	49.0	58.8	60.9	67.5	80.6
17-V			430.5	0.7138	143.9	79.5	110.5	128.2	132.8	139.2	152.9
18-L	662	340	536.7	0.8034	159.8	18.2	26.5	32.5	36.0	41.7	53.7
18-V			409.6	0.7189	141.8	73.5	103.0	120.3	124.3	129.2	145.6
19-L	661	159	594.1	0.8293	162.8	6.7	10.3	13.2	14.5	18.1	24.1
19-V			805.4	0.7382	144.6	56.5	81.5	95.7	99.4	107.8	122.0
20-L	701	603	1191.7	0.7763	155.2	36.0	54.0	63.4	65.8	72.0	85.5
20-V			440.9	0.7339	145.2	85.0	94.0	107.0	110.2	117.2	130.8
21-L	698	547	727.7	0.7840	157.0	31.5	45.5	55.1	57.9	62.8	77.0
21-V			413.7	0.7292	148.0	68.5	96.5	114.5	117.2	125.3	138.5
22-L	699	391	510.0	0.8046	158.5	18.0	27.0	35.0	37.0	42.2	53.5
22-V			629.6	0.7308	149.2	67.5	95.5	112.7	114.7	124.0	138.0
23-L	702	192	452.7	0.8159	158.2	7.0	11.1	13.8	15.5	18.8	25.3
23-V			1054.5	0.7514	151.7	51.5	76.0	89.1	92.1	99.0	112.5
24-L	730	543	419.9	0.7886	160.3	26.0	38.0	48.0	50.6	55.2	67.2
24-V			739.3	0.7437	147.0	56.0	80.5	95.2	98.7	102 7	117.7
25-L	730	598	408.5	0.7827	156.6	31.0	47.0	56.19	59.8	65.0	77.3
25-V			568.8	0.7462	148.2	55.6	79.0	93.5	97.3	103.7	116.7
26-L	667	517	796.9	0.7850	153.9	30.0	45.0	55.0	58.6	64.0	76.0
26-V			476.3	0.7204	143.1	75.0	104.5	122.5	126.5	132.7	145.4
27-L	681	316	245.5	0.8133	161.8	12.0	20.0	26.0	28.2	32.0	42.8
27-V			319.2	0.7299	143.2	63.0	91.5	108.8	113.2	120.0	134.7
28-L	769	168	904.1	0.8307	163.3	...	...	...	3.1	9.8	23.3
28-V			489.0	0.8041	159.9	...	...	...	12.4	30.5	38.6
29-L	759	118	611.0	0.8413	166.1	...	...	...	1.3	5.2	14.0
29-V			1127.0	0.8099	159.8	...	...	...	10.0	24.0	47.8
30-L	820	335	478.0	0.8241	166.1	...	...	...	8.4	16.9	31.0
30-V			1182.0	0.8009	160.7	...	...	...	22.0	37.0	60.0
31-L	800	223	3210.0	0.8290	94.5	...	...	...	2.6	5.8	11.8
31-V			432.0	0.8020	160.2	...	...	...	7.9	31.8	54.8
Fuel oil 3	...	...	....	0.8219	163.7	...	...	...	3.8	13.5	34.0

[a] L = liquid; V = vapor.

TABLE 4
Experimental bubble and dew points of naphtha

Bubble point		Dew point	
Temperature, °F.	Pressure, lb. per sq. in. abs.	Temperature, °F.	Pressure, lb. per sq. in. abs.
385	405	278	92
376	390	345	225
360	325	420	447
333	260		
350	312		

TABLE 5
Calculated equilibrium vaporization constants for combined pentanes, hexanes, and heptanes in naphtha experimental runs

Temperature, °F.	Pressure, lb. per sq. in. abs.	Liquid residue, mole percent of feed	Equilibrium vaporization constants, $K=y/x$		
			Pentanes	Hexanes	Heptanes
365	323	73.6	1.210	0.789	0.551
349	276	40.2	1.287	0.854	0.412
338	240	30.3	1.267	0.743	0.623
347	265	40.2	1.247	0.870	0.466
377	315	36.8	1.222	0.908	0.486
410	452	67.6	1.111	0.930	0.688
402	405	66.8	1.110	0.897	0.714
385	350	45.4	1.178	0.824	0.660
380	320	16.1	1.223	0.828	0.608

The tank is heated by four longitudinal gas burners set 8 in. below the bottom of the tank. The salt bath temperature is taken by two thermocouples. It was found that convection leveled out temperature gradients to within 2°F. Little difficulty was encountered in maintaining constant temperature to ±2° for periods up to one hour. During operation a salt level is maintained that covers the top of the separator to a depth of about ½ in.

Furnace and pump. The furnace and pump were described previously[12].

Coolers. Condensation and cooling of the liquid and vapor streams leaving the separator are accomplished by four coil-in-jacket low-pressure coolers, two connected parallel in each stream. Each of these coolers contains about 25 ft. of ¼ by 5/16-in. copper tubing coiled around a 1¼-in. arbor. These coils are brazed into 3-in. diameter brass jackets about 20 in. long and 1/16 in. thick. City water is supplied to the jackets in flow countercurrent to that of the hot material.

Miscellaneous. The thermocouples used are made of chromel-alumel thermocouple wire and are calibrated against a standard platinum and platinum-rhodium couple, calibrated by the National Bureau of Standards. The cold junctions are immersed in a bath of finely chipped ice, and all are connected to a central switch. The millivolts developed by the thermocouples are read

ata on

equilibrium vaporizations at high temperature

Fractional Analyses in Cubic Centimeters							Weight of Successive Fractions in Grams									
400–450° F.	450–500° F.	500–550° F.	550–600° F.	600–650° F.	650–700° F.	700–750° F.	0–25 cc.	25–50 cc.	50–75 cc.	75–100 cc.	100–125 cc.	125–150 cc.	150–175 cc.	175 cc. Residue	Total	Loss
106.2	119.4	134.6	154.3	174.7	186.2	200.3	15.75	15.98	17.70	19.14	20.05	20.54	20.96	13.72	5.40	149.25	3.25
152.8	162.0	172.2	181.7	190.2	196.0	204.5	15.79	15.74	15.76	16.68	17.97	19.13	20.15	14.77	4.70	140.69	2.71
106.2	120.0	137.3	164.2	181.2	192.5	200.2	15.13	16.17	17.86	19.26	20.03	20.54	21.24	18.02	4.90	153.15	..
160.0	169.6	179.1	188.3	195.7	200.8	206.2	15.63	15.73	15.76	16.80	17.81	18.84	19.89	16.64	5.40	142.50	1.40
72.7	86.7	104.9	136.2	166.4	184.7	198.9	15.76	17.90	19.54	20.17	20.59	20.90	21.24	15.09	5.38	156.55	0.95
170.5	180.5	189.7	197.0	201.9	205.7	210.0	15.72	15.76	15.82	16.56	17.60	18.39	19.57	20.44	4.90	150.63	..
41.9	53.8	73.2	113.6	151.9	177.1	200.5	17.15	19.73	20.38	20.63	20.92	21.17	21.34	17.43	4.70	163.44	0.36
147.7	158.4	170.3	181.7	191.1	196.9	200.8	15.68	15.65	16.07	17.28	18.34	18.53	20.22	15.51	3.65	140.94	3.86
85.5	100.4	117.3	144.5	171.3	187.7	200.1	15.85	17.04	19.04	19.99	20.34	20.68	21.04	15.92	5.10	155.00	1.00
161.6	170.9	179.7	187.6	194.2	197.9	201.9	15.54	15.56	15.63	16.65	17.69	18.75	19.76	7.20	15.60	142.38	0.82
95.8	108.7	124.8	150.0	174.0	189.7	200.2	15.65	16.38	18.33	19.60	20.33	20.66	21.10	13.76	7.90	153.71	0.99
149.4	159.3	170.3	181.8	191.1	196.4	200.0	15.64	15.66	15.91	17.00	18.14	19.36	20.31	13.17	7.40	142.57	0.73
88.6	102.0	117.2	141.7	168.3	185.2	200.5	15.68	16.64	18.58	19.83	20.46	20.76	21.16	12.85	9.40	155.36	0.54
142.8	153.2	162.8	176.3	189.0	196.5	200.1	15.63	15.65	15.97	17.18	18.34	19.56	20.40	15.08	6.55	144.35	0.55
96.5	109.8	123.8	148.6	171.8	187.9	199.8	15.75	16.11	18.29	19.50	20.10	20.62	21.38	15.80	5.6	153.15	0.55
137 4	147.0	157.7	172.5	186.8	194.7	199.9	15.49	15.58	15.97	17.30	18.91	19.59	20.30	21.30	..	144.65	0.05
74.5	88.2	104.7	133.0	165.1	183.6	201.7	15.64	17.55	19.31	20.24	20.51	20.91	21.20	14.27	8.60	158.22	0.88
144.3	154.3	164.8	178.4	191.1	192.8	201.3	15.72	15.73	16.02	17.18	18.12	19.58	20.40	15.92	6.15	144.82	1.08
57.0	70.5	85.6	114.9	151 5	176.5	202.7	16.14	18.42	19.96	20.50	20.78	21.06	21.28	15.45	9.30	162.89	0.41
138.8	148.8	160.2	175.0	188.3	196.0	201.2	15.65	15.71	16.10	17.41	18.57	19.76	20.49	15.65	6.00	145.33	0.57
110.8	123.2	137.1	157.2	177 2	191.6	201.3	15.58	15.84	17.37	18.82	19.86	20.44	20.87	15.30	6.60	150.68	1.16
181.2	185.8	189.9	193.2	196.0	198.8	201.4	15.62	15.63	15.64	15.69	16.68	17.57	18.56	14.31	8.10	137.82	..
78.9	93.5	111.7	140.8	168.2	185.5	200.6	15.64	17.48	19.21	19.96	20.42	20.10	20.96	22.55	..	156.92	0.58
178.0	183.7	188.9	192.7	195.7	198.2	200.8	15.64	15.69	15.69	16.04	16.95	17.94	19.02	13.05	8.25	138.28	0.32
52.1	67.7	87.5	121.7	158.5	181.5	199.5	16.48	19.15	20.02	20.46	20.72	20.98	21.24	20.95	..	160.00	0.70
170.3	178.5	185.0	190.3	193.7	197.1	199.9	15.65	15.65	15.68	16.35	17.30	18.24	19.44	20.60	..	138.90	0.50
79.1	92.6	109.2	136.7	166.3	185.3	201.9	15.59	17.13	19.08	20.08	20.52	20.84	21.17	22.05	..	156.44	0.71
141.3	151.7	163.4	177.9	189.2	196.6	201.9	15.61	15.61	16.03	17.30	18.47	19.67	20.46	16.71	6.45	146.30	0.45
84.1	100.0	117.5	145.7	172.7	189.8	199.3	15.61	17.25	19.09	19.92	20.42	20.71	21.09	15.68	5.60	155.37	0.53
181.0	187.3	191.4	194.5	197.1	199.4	201.7	15.62	15.62	15.62	15.80	16.84	17.72	18.83	21.70	..	137.74	0.66
45.3	62.3	83.0	118.7	158.5	181.6	200.3	17.26	19.51	20.21	20.42	20.69	20.97	21.22	22.25	..	162.53	0.27
164.2	174.7	183.2	189.9	193.0	197.2	199.8	15.65	15.68	15.69	16.80	17.85	18.92	19.77	16.30	8.10	144.76	..
93.6	108.5	128.1	156.3	178.9	192.8	199.4	15.73	16.67	18.68	19.69	20.37	20.64	21.05	16.10	5.82	154.73	0.27
162.3	171.6	180.6	189.6	196.7	200.0	202.3	15.65	15.74	15.71	16.73	17.79	18.86	19.88	17.16	5.40	142.91	1.00
68.5	84.3	102.7	134.6	162.4	184.2	200.1	15.96	18.56	19.86	20.18	20.51	20.77	21.16	15.53	6.00	158.52	1.28
156.3	166.3	176.2	187.1	192.2	199.7	201.0	15.63	15.63	15.83	16.90	18.11	19.15	20.05	17.16	4.60	143.06	..
33.0	46.8	66.8	101.5	143.9	112.6	197.7	17.88	20.03	20.49	20.68	21.00	21.20	21.37	12.14	7.53	162.29	0.51
135.3	149.1	164.0	178.9	190.7	195.6	197.7	15.59	15.62	16.57	18.00	19.12	19.90	20.47	14.72	4.10	144.09	0.51
98.5	113.5	130.7	156.5	179.5	194.3	200.2	15.62	16.36	18.38	19.53	20.13	20.58	20.93	16.22	6.03	153.79	1.411
142.0	153.5	165.8	179.9	191.5	197.0	199.7	15.59	15.52	16.19	17.47	18.70	19.76	20.59	14.94	5.65	144.41	0.79
90.3	105.5	128.0	152.8	178.2	193.7	201.8	15.66	16.99	18.90	19.81	20.36	20.67	21.24	15.82	7.30	156.75	0.25
150.0	161.2	172.6	187.2	195.5	201.5	204.8	15.60	15.61	15.91	17.17	18.38	19.40	20.14	17.53	7 70	147.44	0.51
66.7	82.8	102.1	139.2	168.9	188.3	198.6	16.00	18.54	19.80	20.21	20.64	20.96	21.09	13.85	6.80	157.89	0.61
150.0	162.4	174.2	189.5	199.7	204.2	207.0	15.64	15.66	16.05	17.34	18.51	19.44	20.26	20.04	15.80	148.73	0.43
33.8	44.8	59.9	89.3	130.2	153.6	194.0	16.23	19.48	20.01	20.97	21.04	20.98	20.99	11.64	6.37	157.71	0.49
125.3	139.0	153.1	170.3	187.3	196.7	203.3	15.61	15.65	16.91	18.39	19.44	20.16	20.56	17.72	6.90	151.34	0.36
78.6	94.2	113.3	142.3	171.2	190.2	205.1	15.81	17.33	19.18	19.96	20.44	20.70	21.06	15.78	9.20	159.46	0.84
129.2	141.5	154.5	170.0	185.0	194.2	198.5	15.72	15.74	16.61	18.04	19.29	20.09	20.65	14.79	5.90	146.62	0.38
86.7	103.0	119.1	144.8	169.2	186.8	201.8	15.61	16.73	18.72	19.80	20.38	20.66	21.58	15.71	7.90	157.08	..
128.4	140.5	153.3	170.0	185.9	195.1	199.6	15.69	15.73	16.61	18.16	19.35	20.15	20.72	15.73	5.80	147.93	0.27
87.8	102.3	119.2	145.6	170.2	187.6	197.7	15.60	16.85	18.80	19.82	20.37	20.69	21.08	14.35	5.80	153.36	0.54
155.6	166.0	174.9	184.6	191.9	196.5	200.5	15.63	15.64	15.68	16.80	17.92	19.12	20.00	9.62	12.70	143.11	..
55.2	70.7	90.2	123.2	158.8	182.0	200.8	16.47	19.19	20.04	20.44	20.66	20.98	21.26	22.30	.	161.33	0.47
145.3	156.5	168.4	181.0	191.7	195.0	197.7	15.63	15.68	16.18	17.43	18.58	19.58	20.34	15.07	4.40	142.88	0.32
38.1	57.5	78.3	106.1	149.0	175.0	198.3	18.99	19.84	20.22	20.56	20.77	21.04	21.33	12.15	7.70	162.61	0.69
82.6	108.6	130.9	161.0	182.2	192.5	199.8	18.38	19.18	19.85	20.06	20.27	20.55	20.90	13.72	6.25	159.16	0.74
24.7	40.0	60.2	100.2	142.0	174.1	199.1	19.52	20.23	20.51	20.76	21.06	21.27	21.43	20.70	..	165.49	0.61
69.6	94.3	118.7	150.5	176.2	189.9	198.1	18.54	19.28	19.79	20.15	20.68	21.04	21.07	12.83	5.70	159.07	0.73
46.2	66.1	88.2	124.2	159.0	180.3	202.2	18.66	18.72	20.26	20.56	20.74	21.08	21.38	22.70	..	165.10	1.00
81.0	103.8	126.6	155.6	177.0	189.0	202.3	17.72	19.04	19.45	19.94	20.26	20.59	20.95	20.10	..	158.06	2.64
19.2	28.0	40.0	58.3	78.5	93.1	114.7	19.47	20.56	21.07	22.87	9.80	....	....	....	..	93.76	0.74
74.0	97.6	119.3	148.6	169.0	186.9	201.0	17.93	19.10	19.69	20.09	20.41	20.57	21.11	19.20	..	158.14	2.06
53.1	74.6	98.0	134.2	167.9	187.8	201.0	18.99	19.58	20.07	20.33	20.90	20.94	21.16	21.65	..	163.63	0.07

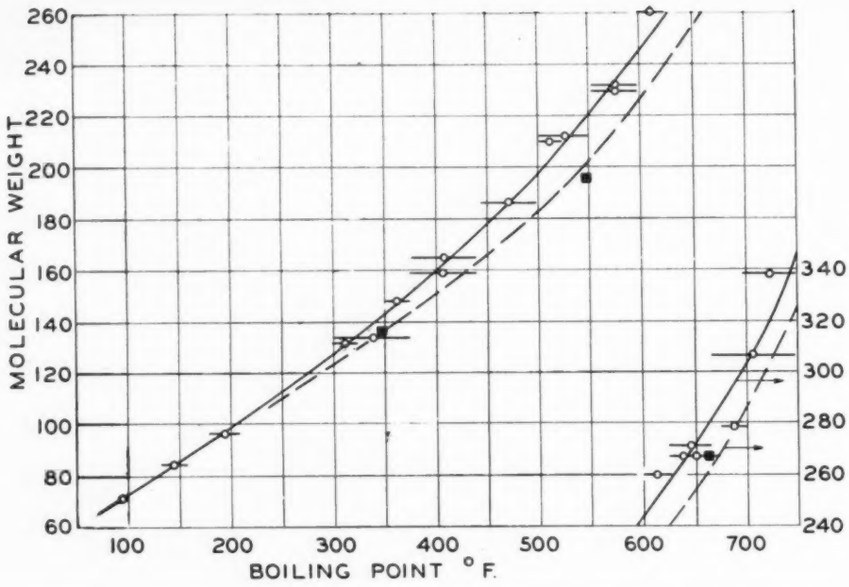


Fig. 4. Molecular weight as a function of boiling point. Squares indicate cracked samples; lines through circles indicate boiling range of distillate cuts

TABLE 7

Experimental bubble and dew points of mixtures of light naphtha and domestic furnace oil

Bubble point			Dew point		
Temperature, °F.	Pressure, lb. per sq. in. abs.	Light naphtha, volume percent	Temperature, °F.	Pressure, lb. per sq. in. abs.	Light naphtha, volume percent
636	672	40.3	715	653	40.3
566	582	40.3	727	625	40.3
579	473	34.0	732	627	37.5
667	618	34.0			

by a Leeds and Northrup portable precision potentiometer. Temperature measurements are accurate to $\pm 1°$F. Three Ashcroft pressure gauges are used, having ranges of 0-1000, 0-3000, and 0-5000 lb. per sq. in. The 1000-lb. gauge is connected to the distillate line from the separator. This gauge is calibrated on a dead weight tester before and after use.

Stainless steel Metric valves made by the American Meter Company, Inc., are used and packed with Allpax No. 2 high-temperature packing.

Chromel wire, No. 22 gauge, is wound on a base of alundum cement around the furnace transfer line to reduce heat losses. Twenty-five feet of wire are wound into a length of about 18 in. on a 1-in. diameter and connected through a slide wire resistance to 110-volt alternating current. Another such winding is placed on the distillate transfer line from the separator in order to eliminate any refluxing which may tend to take place in that line because of heat losses.

All high-pressure lines are piped through the high-pressure fittings of the type shown in Fig. 3, and the piping itself is made of seamless chromium-molybdenum tubing, 9/16 by 3/16 in., as supplied by the American Instrument Company. The fittings and piping are tested hydraulically to 15,000 lb. per sq. in. at room temperature, without leakage.

Experimental Technique

Immediately before a run the equipment is tested under flow conditions to pressures from 1500 to 2000 lb. per sq. in. at room temperature.

With the cold oil circulating through the system, full power is supplied to the furnace. The salt mixture is crushed and added to the constant-temperature tank. The gas burners beneath are turned on. From this point until the completion of the run, temperatures, pressures, and amperages are read regularly at 15-minute intervals.

The furnace is leveled out or placed on stream at the desired temperature by cutting resistance into the furnace circuit. The salt bath temperature is adjusted and maintained within $\pm 3°$F. of the separator temperature. Operation is maintained constant throughout the system for at least 15 minutes. Just prior to sampling, the drawoff lines are flushed.

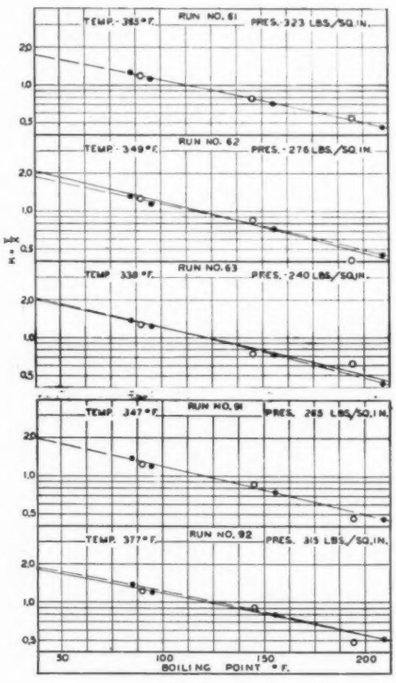
When the operation has been properly leveled out, as outlined above, samples are taken from the atmospheric separators by closing the lines to the recycle tank and withdrawing the entire liquid and vapor streams into suitable bottles, meanwhile holding the liquid levels in the atmospheric separators constant by proper manipulation of the drawoff valve. Throughout the sampling operation the liquid level is maintained constant in the high-pressure separator with utmost care. At the conclusion of sampling, the liquid levels in high-pressure and atmospheric separators must be identical with those at the beginning of sampling. Temperatures and pressures in the separator and salt bath are read continually during sampling.

The most convenient sequence in the taking of samples at isothermal points is to determine the bubble point first and then to take samples at successively lower pressure until the dew point is reached.

Bubble and dew point determinations. Bubble point determinations may be made by closing vapor valve C (Fig. 1) and maintaining a constant liquid level in the separator when operating isothermally. The maximum pressure obtained without an increase in liquid level is the bubble point pressure at that temperature.

Dew point pressures may be determined as follows: Both the liquid-line B and vapor-line C valves are opened to insure the complete absence of liquid in the separator. The liquid level bridge is adjusted to give a balance point in the vapor phase. Liquid valve B is then closed and vapor valve C gradually closed to increase the pressure iso-

Fig. 5. Calculated equilibrium volatility constants as a function of volumetric average boiling point of the components for runs on the light naphtha



thermally. At the dew point pressure the presence of liquid is indicated by a sudden unbalance of the liquid level indicator.

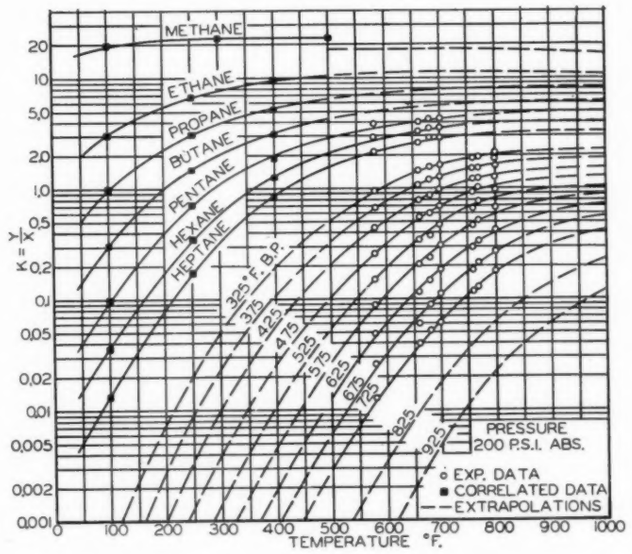
Retrograde dew points are somewhat more difficult to determine. The separator is operated under conditions above the critical temperature and at approximately the critical pressure where the stock is in the single-phase region. Liquid-line valve B is cracked at successive short intervals without allowing the separator pressure to drop. The liquid level indicator is adjusted as before to give a balance in the single phase. The pressure is now allowed to fall slowly by gradually opening vapor valve C.

At the dew point pressure, liquid will separate out of the uniform phase, and its presence will be shown on the indicator by a sudden deflection. Although this deflection is not large, the sharpness with which it takes place is easy to observe.

Materials

A naphtha, a distillate furnace oil, and mixtures of the two were used as feed.

The naphtha was obtained through the courtesy of the Phillips Petroleum Company, and is their "butane-free,



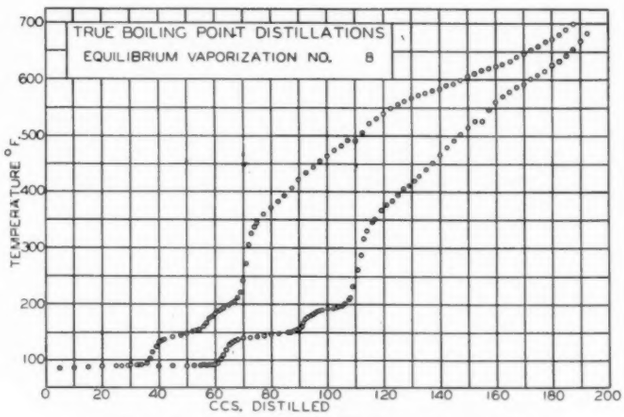


Fig. 6. Analytical distillations for run 8

Fig. 9 (left). Ideal equilibrium constants as a function of temperature at 200 lb. per sq. in. abs. pressure

Fig. 8 (below). Equilibrium volatility constants for two complex mixtures plotted as a function of pressure

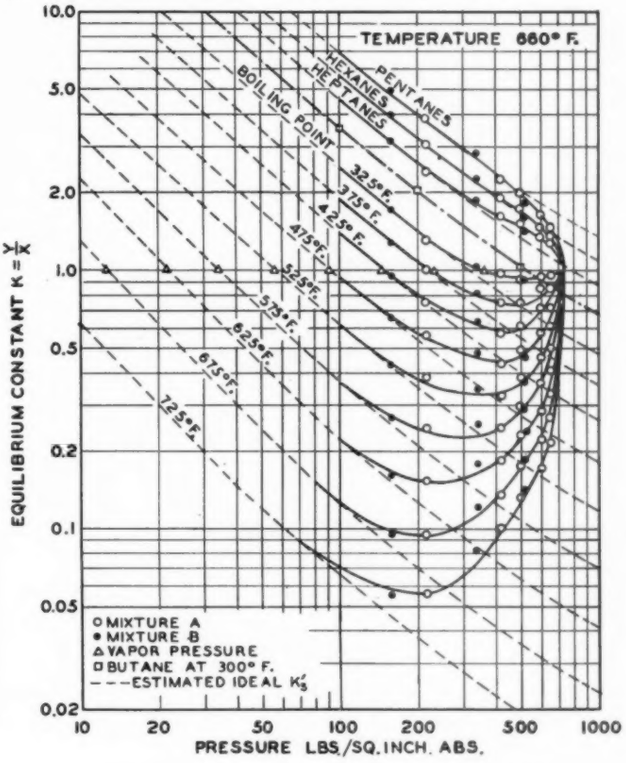
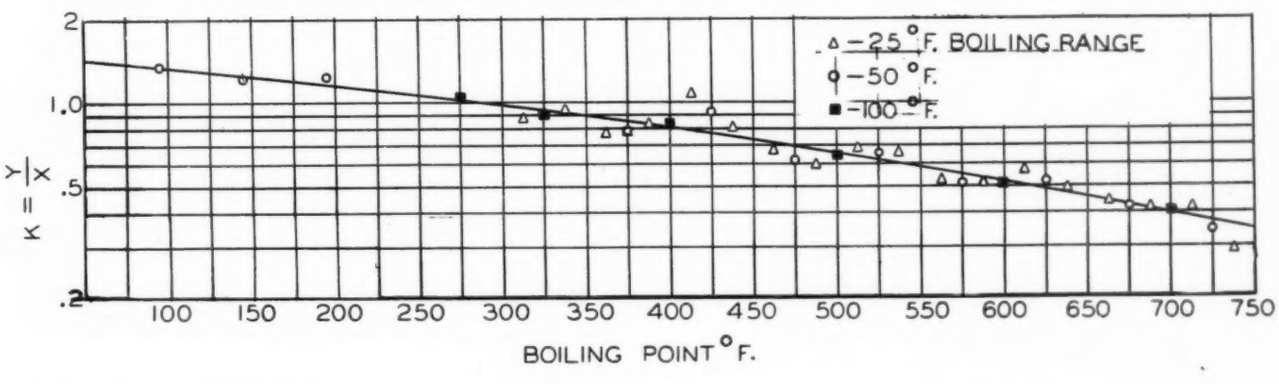


Fig. 7. Equilibrium volatility constants as a function of volumetric average boiling point for run 8



oil-free" cut from natural gasoline. The naphtha contains *iso-* and normal pentanes, hexanes, and heptanes with small amounts of aromatics and unsaturates. The pertinent physical data are listed in Table 1.

The furnace oil was obtained locally and is known as Domestic Furnace Oil No. 3. The physical data are listed in Table 2.

Analyses

The samples of the liquid and condensed vapor streams were analyzed by fractional distillation in a Podbielniak high-temperature column[17]. The column was operated with a 6.5-mm. distillation tube, and the distillations were carried out at atmospheric and at 40 mm. pressure. A calibrated copper-constantan thermocouple was used for measuring the overhead temperatures.

In the analyses 200-cc. samples were weighed into the distillation flask and the flask was sealed to the column by a ground-glass joint with Merco lubricant No. 650, size B, as the sealing medium. The overhead product of the analytical distillation was collected in 25-cc. cuts whose densities were determined at a measured temperature by a Westphal balance. Temperature readings were taken at 2.5-cc. intervals.

In the analyses of the light naphtha the distillation rate was set at a maximum of 2.5 cc. per min. on definite plateaus and not over 1.00 cc. per min. at the cut points between pentane and hexane and between hexane and heptane. At no time during the distillations was the rate allowed to fall below 0.50 cc. per min. At cut points the minimum reflux ratio permissible was 10 to 1, this ratio being determined by counting the number of drops returning to the still and the number being taken off overhead.

The distillation analysis of the furnace oil was conducted partially under atmospheric pressure and partially under vacuum.

After some experimentation it was found that the most satisfactory results were obtained by operating the column at a rate of 1.00 to 1:25 cc. per min. at atmospheric pressures up to overhead temperatures of about 500°F. For boiling points above 500°F. the column was operated under a pressure of about 35-40 mm. of mercury at a rate of 1.25 cc. per min.

If the rate was allowed to drop below 1.00 cc. per min., at overhead temperatures of 400°F. upward at atmospheric pressure and of 300°F. upward under vacuum, excessively low overhead temperatures were recorded. A rate of 1.00 cc. per min. was therefore set as a minimum, 1.50 cc. per min. as a maximum rate.

In order to obtain consistent results, the analytical procedure was rigidly standardized as to distillation rate, weighing out samples, taking of gravities, recording of temperatures, etc.

An illustration of the reproducibility of these data is presented in Table 2 which shows two distillations of the furnace oil run at intervals of about two months.

Molecular Weight Determination

The molecular weights of various cuts from the analytical distillations were determined by the freezing point depression method[26], using as a solvent Baker's analyzed benzene saturated with distilled water.

Molecular weights were first determined on successive 12.5 percent by volume cuts from the analytical distillation of the furnace oil. As the boiling range of these cuts was from 35° to 100°F., additional determinations were made of furnace oil cuts of 25°F. boiling range.

TABLE 8
Sample calculation for Run 8

Fraction, °F.	Liquid sample 8-L: Cumulative vol., cc.	Cumulative wt., grams	weight by cut, grams	mol. wt., Fig. 4	Mole, per cut	Moles, percent (x)	Vapor by similar procedure on 8-V, mole percent (y)	K = y/x	Smoothed K's, Fig. 7
Pentanes	38.0	24.5	24.5	72	0.3405	31.49	43.78	1.389	1.38
Hexanes	56.5	37.2	12.7	85.5	0.1486	13.74	16.72	1.217	1.28
Heptanes	68.8	45.9	8.7	97	0.0897	8.30	10.25	1.237	1.19
209–300	71.8	48.2	2.3	115	0.0200	1.85	2.13	1.150	...
300–350	75.9	51.3	3.1	134	0.0232	2.15	1.95	0.908	0.93
350–400	86.5	59.5	8.2	150	0.0547	5.06	3.95	0.779	0.85
400–450	96.5	67.4	7.9	168	0.0470	4.35	4.00	0.921	0.75
450–500	109.8	78.2	10.8	187	0.0578	5.35	3.30	0.617	0.68
500–550	123.8	89.2	11.1	208	0.0534	4.93	3.16	0.641	0.60
550–600	148.6	109.7	20.4	231	0.0884	8.18	4.14	0.506	0.54
600–650	171.8	129.5	19.8	257	0.0771	7.13	3.72	0.522	0.48
650–700	187.9	143.4	13.9	286	0.0486	4.50	1.88	0.418	0.42
700–750	198.8	153.7	10.3	320	0.0322	2.98	1.02	0.343	0.37
				Total	1.0812	100.1	100.0		

TABLE 9
Leveled values of calculated equilibrium vaporization constants

Run No.	Mixture	Temperature, ° F.	Pressure, Lb./Sq. In. Abs.	$K = y/x$, Equilibrium Constants: 86–95° F. (pentanes)	135–156° F. (hexanes)	175–209° F. (heptanes)	300–350° F.	350–400° F.	400–450° F.	450–500° F.	500–550° F.	550–600° F.	600–650° F.	650–700° F.	700–750° F
1	A	662	648	1.48	1.36	1.26	0.96	0.85	0.72	0.61	0.50	0.41	0.335	0.270	0.217
2	A	659	596	1.63	1.48	1.33	0.95	0.85	0.71	0.57	0.46	0.363	0.284	0.221	0.171
3	A	656	420	2.25	1.90	1.60	0.97	0.75	0.57	0.435	0.325	0.245	0.182	0.135	0.100
4	A	657	216	3.85	3.03	2.40	1.30	1.00	0.75	0.56	0.382	0.247	0.152	0.094	0.056
5	A	663	503	2.00	1.72	1.50	0.92	0.75	0.61	0.49	0.385	0.300	0.230	0.175	0.131
6	A	682	596	1.57	1.41	1.27	0.93	0.82	0.70	0.59	0.49	0.41	0.331	0.269	0.217
7	A	699	595	1.50	1.37	1.23	0.94	0.84	0.75	0.68	0.58	0.49	0.41	0.33	0.255
8	A	700	650	1.38	1.28	1.19	0.93	0.85	0.75	0.68	0.60	0.54	0.48	0.42	0.37
9	A	700	501	1.86	1.63	1.43	0.99	0.84	0.69	0.56	0.46	0.369	0.295	0.231	0.188
10	A	700	344	3.00	2.58	2.04	1.24	0.99	0.76	0.58	0.43	0.32	0.238	0.173	0.127
11	A	575	498	1.65	1.35	1.10	0.63	0.51	0.40	0.321	0.252	0.197	0.152	0.117	0.088
12	A	583	340	2.49	1.91	1.44	0.70	0.52	0.38	0.272	0.190	0.140	0.098	0.069	0.048
13	A	580	205	3.60	2.72	2.01	0.92	0.67	0.47	0.31	0.20	0.125	0.078	0.038	0.0215
14	A	710	546	1.69	1.50	1.32	0.96	0.83	0.71	0.61	0.52	0.435	0.360	0.293	0.238
15	B	580	352	2.40	1.85	1.41	0.70	0.52	0.38	0.275	0.20	0.143	0.103	0.072	0.050
16	B	583	147	4.81	3.60	2.65	1.20	0.87	0.60	0.41	0.240	0.134	0.072	0.0375	0.0195
17	B	660	517	1.79	1.58	1.40	0.91	0.74	0.60	0.46	0.37	0.293	0.232	0.182	0.141
18	B	662	340	2.83	2.28	1.87	1.02	0.81	0.63	0.475	0.345	0.250	0.178	0.12	0.082
19	B	661	159	5.05	4.00	3.17	1.70	1.29	0.95	0.66	0.43	0.27	0.16	0.095	0.055
20	B	701	603	1.43	1.31	1.22	0.95	0.85	0.75	0.67	0.58	0.49	0.41	0.325	0.252
21	B	698	547	1.65	1.48	1.31	0.96	0.84	0.71	0.59	0.48	0.385	0.305	0.241	0.189
22	B	699	391	2.47	2.07	1.76	1.09	0.88	0.69	0.54	0.405	0.306	0.238	0.169	0.124
23	B	702	192	4.50	3.70	2.90	1.70	1.30	1.04	0.73	0.50	0.35	0.229	0.138	0.090
24	B	730	543	1.73	1.53	1.37	0.98	0.86	0.78	0.65	0.56	0.475	0.400	0.341	0.284
25	B	730	598	1.41	1.29	1.20	0.95	0.86	0.78	0.69	0.62	0.55	0.48	0.425	0.363
26	B	667	517	1.83	1.60	1.38	0.95	0.77	0.64	0.52	0.42	0.323	0.250	0.190	0.142
27	B	681	316	2.92	2.40	1.98	1.13	0.90	0.70	0.53	0.395	0.285	0.203	0.130	0.084
28	Furnace oil	769	168	..	..	..	2.25	1.80	1.44	1.27	0.88	0.66	0.47	0.337	0.233
29	Furnace oil	759	118	..	..	..	2.90	2.35	1.85	1.43	1.04	0.72	0.51	0.35	0.228
30	Furnace oil	820	335	..	..	..	1.50	1.31	1.16	0.99	0.83	0.68	0.55	0.45	0.37
31	Furnace oil	800	223	..	..	..	1.88	1.63	1.40	1.13	0.90	0.70	0.55	0.42	0.322

Determinations were also made on the hexane and heptane fractions and on cuts from material subjected to cracking temperatures.

The average molecular weight of the furnace oil was calculated to be 206, from the analytical distillation and the molecular weights of cuts from the analytical distillation; it was also determined experimentally and found to be 207. The results of the molecular weight determinations are listed in Table 3 and plotted in Fig. 4.

Preliminary Work

A naphtha similar to that of Table 1, dyed with Sudan Red III, was used to determine the amount of entrainment, if any, under various conditions of temperature and pressure approaching the critical point, and to determine the limits of satisfactory operation of the liquid level indicator. The stability and volatility of the dyestuff were tested in an A. S. T. M. distillation of a dyed kerosene. It was found to be stable and nonvolatile at temperatures up to 500°F.

The naphtha-dye mixture was fed at rates from 2.9 to 8.8 gal. per hour and with volume in the vapor phase up to 90 percent. No trace of color in the vapor stream was observed below about

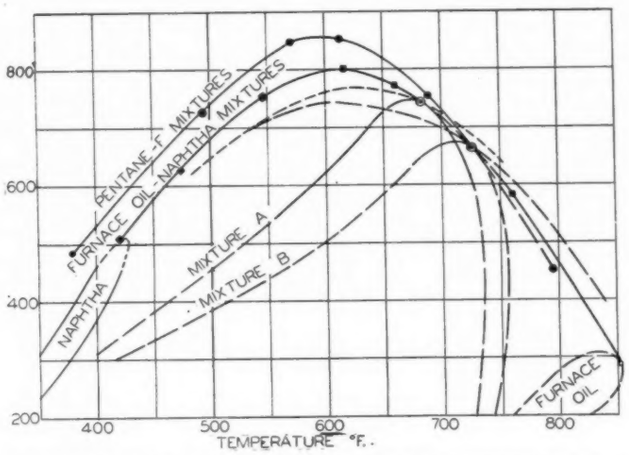


Fig. 10 (left). Critical loci for mixtures of furnace oil and naphtha

Fig. 11. Minimum value for the equilibrium constant as a function of the ratio between the convergence pressure and the vapor pressure of the component

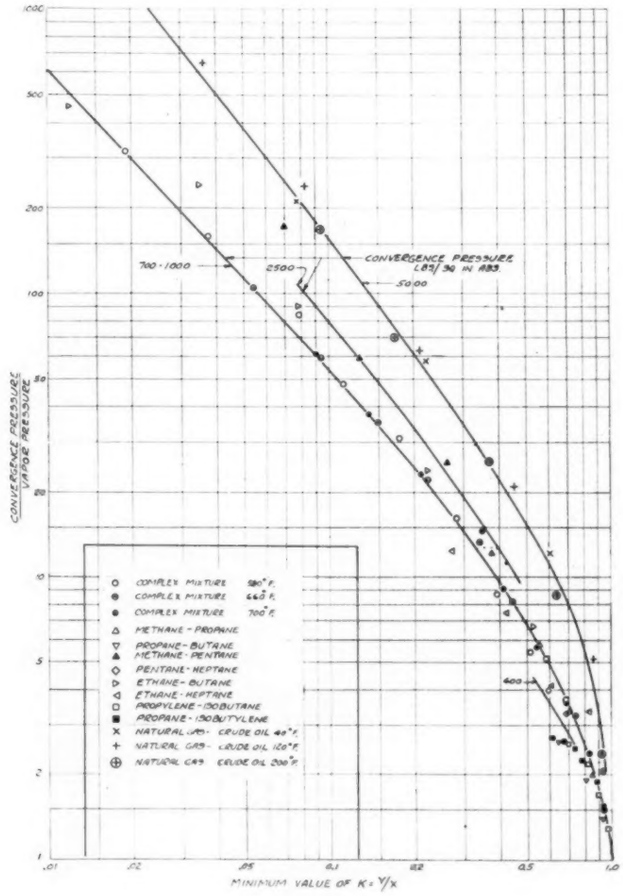
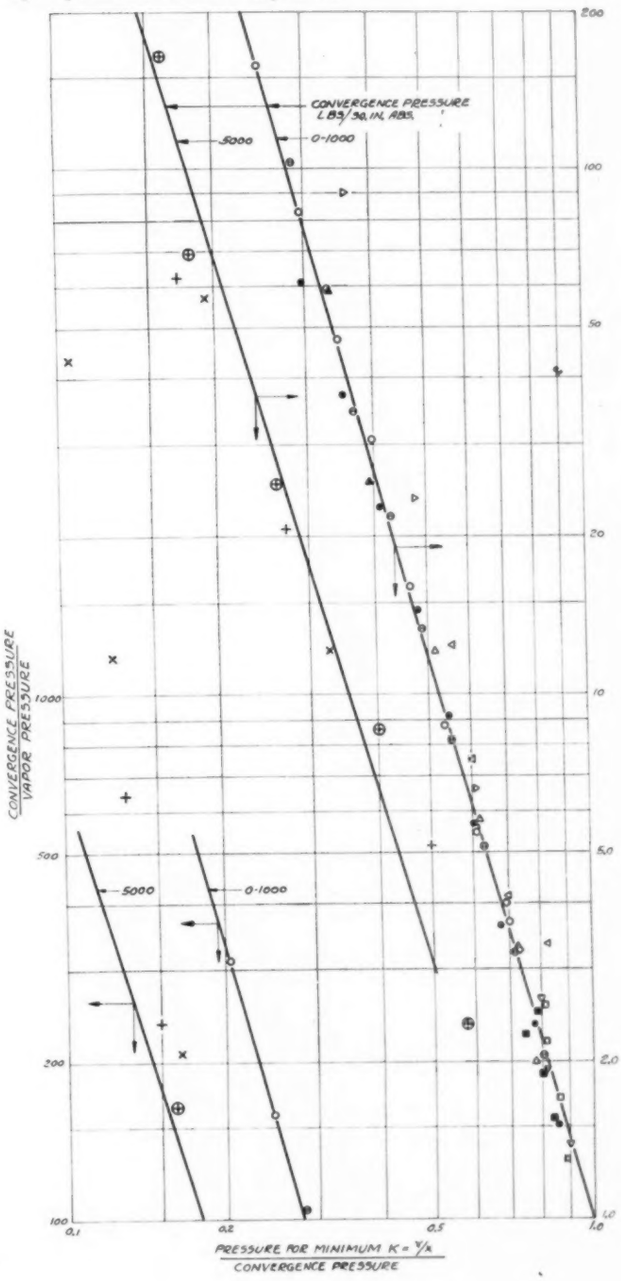


Fig. 12 (below). Ratio of the pressure at which the equilibrium constant is at a minimum value to the convergence pressure as a function of the ratio of the convergence pressure to the vapor pressure of the component


CONVERGENCE PRESSURE / VAPOR PRESSURE
PRESSURE FOR MINIMUM K = Y/x / CONVERGENCE PRESSURE
CONVERGENCE PRESSURE LBS/SQ IN ABS.
5000
0-1000

450 lb. per sq. in. abs. pressure and 420°F. The computed critical point of this naphtha was 422°F. and 508 lb. per sq. in. abs. As the critical point was more closely approached, the amount of coloration grew progressively greater. However, this coloration does not necessarily indicate entrainment since the dye may be present in the vapor phase due to the solubility relations in the region of the critical point.

Bubble points and dew points were determined on the naphtha of Table 1 as described, with results given in Table 4. As a means of indicating the attainment of equilibrium conditions between the liquid and vapor phase, runs were made at the temperatures and pressures indicated in Table 5, and samples were taken and analyzed in a high-temperature Podbielniak fractionating column, as described. The results are expressed in terms of equilibrium vaporization constants, K, defined as the mole fraction in the vapor phase divided by the mole fraction in the liquid phase[25] for the mixed pentanes, hexanes, and heptanes as shown in Table 5.

The data for the first five points, which are at sufficiently low pressure so that equilibrium constants computed from ideal solution relations would apply, are plotted in Fig. 5 as a function of boiling point. The open circles represent the experimental data from Table 5 through which the solid line has been drawn. The solid circles represent the ideal equilibrium constants, based on recently reviewed equilibrium data[2]. The agreement is excellent in all cases except for a few points for heptane, which are considered within the experimental analytical error.

The last four runs shown in Table 5 were made at higher pressures, and the values for the equilibrium constants are affected by proximity to the critical conditions.

The conclusions from these tests are that the apparatus separates efficiently between liquid and vapor, giving vapor free from entrainment over the range in which the liquid level indicator functions satisfactorily, and that the vapor and liquid as removed from the separator are in equilibrium at the temperature and pressure existing therein.

As a check of the overall accuracy in sampling and analysis, the composition of the material fed to the furnace was computed by adding together the compositions of the liquid and vapor samples, with results that agreed within ±3 percent of the amount of components known to be present in the feed.

High-Temperature Equilibrium Vaporization

Runs 1 to 14 (Table 6) were made on a mixture of the light naphtha of Table 1 and the furnace oil of Table 2, containing about 45 percent by volume of the light naphtha and identified as mixture A. Runs 15 to 27, inclusive, were made on a different mixture of the same materials (about 35 percent by volume of the light naphtha) known as mixture B. Runs 28 to 31, inclusive, were made on the furnace oil of Table 2.

Runs 1 to 27, on mixtures A and B, were all made at temperatures below 750°F., and no appreciable cracking or decomposition was noted in any case so that it was possible to make material balances combining the vapor and liquid samples to check the feed composition. Only four runs were made using unblended furnace oil because this material was found to be unsatisfactory for investigating vapor-liquid equilibria, and the temperatures used in runs 28 through 31 were so high that a small amount of cracking occurred in all cases.

Bubble points and dew points of similar mixtures were determined as reported in Table 7.

Equilibrium Volatility Constants

The method of calculating the values for the equilibrium constants can be best explained by an example. The Podbielniak analytical distillation curves of the liquid and vapor samples obtained from 8 are plotted in Fig. 6. The pentane, hexane, and, to a lesser degree, the heptane fractions are easily identified, and these components are treated as such in the computation.

The analytical distillation of the furnace oil fraction gives a smooth curve because of the large number of compounds present. It is therefore necessary to adopt arbitrary components in order to treat the furnace oil fractions in the same manner as the components present in the light naphtha. As indicated in Table 8, these arbitrary components are taken as having a 50°F. boiling range, beginning with 350°F.

By means of the data given in Table 6 and the molecular weights of Fig. 4, it is possible to compute the mole percent of the various components in the liquid as was done in Table 8. A similar procedure may be applied to the analytical data for the corresponding vapor sample with results as given in column 8 of Table 8.

The indicated value for the equilibrium constants is then readily obtained by dividing the mole fraction in the vapor (column 8) by the corresponding mole fraction in the liquid (column 7); the results are listed in column 9.

As a means of leveling the computed equilibrium constants (column 9) and also as a means of comparing the results obtained when using arbitrary components of different boiling ranges, Fig. 7 was prepared to show the effect of arbitrary components of 25° and 100°F. boiling ranges on the equilibrium constants as indicated.

The greater sensitivity of the narrow-boiling-range components to analytical errors is clearly indicated in Fig. 7. Slight analytical inaccuracies caused the inclusion of too little or too much material in a given boiling range. When the boiling range is narrow and the quantity of material included in the component is small, these slight inaccuracies have a relatively large effect on the value of the equilibrium constant. Usually in such cases, where too much material is included in one fraction, one of the adjacent fractions will have too little material. This will cause the computed values for the equilibrium constants of the different components to fluctuate above and below the correct figure. This tendency of the narrow-range components is clearly indicated by the triangles representing the 25°F. components in Fig. 7.

Components of 50°F. boiling range contain sufficient material so that the slight analytical inaccuracies are not exaggerated, and a more reliable curve may be drawn through these data than when using the extremely narrow-boiling components.

By following this procedure for all of the runs given in Table 6, the values for the equilibrium constants of the various components were obtained as given in Table 9.

Discussion of Results

The use of equilibrium volatility constants derived from the concept of ideal solutions[25] has met with considerable success when the conditions do not approach the critical region. As indicated[7], the values for the equilibrium constants of all components become unity at the critical point. The effect of critical conditions in modifying the values of the ideal equilibrium constants may extend down to relatively low pressures, particularly in the case of complex mixtures of relatively wide boiling range.

The basic concept of the use of equilibrium constants is that the value for any particular component is determined by the temperature and pressure. This condition is strictly true for all binary systems. From the phase rule it is clear that a two-component system in equilibrium in two phases has two degrees of freedom, or is completely defined when any two independent variables are fixed. The independent variables are the composition of each phase, the temperature, and the pressure. Therefore, if the temperature and pressure are fixed, the compositions of the liquid

and the vapor phases are determined, and the value for the equilibrium volatility constant ($K = y/x$) is also determined for each of the two components.

In the case of a complex mixture containing many components, the compositions of the liquid and vapor phases are not defined solely by the temperature and pressure, as the number of degrees of freedom from the phase rule is equal to the number of components. It has been found that the values for the vaporization equilibrium constants are generally the same for the same components in different mixtures except in so far as they are influenced by approach to the critical conditions.

Although some attempt has been made[5] to correlate the behavior of equilibrium constants in the critical region, there is still no entirely satisfactory method for obtaining these values. The data obtained in this investigation, together with published data on various binary systems, provide a basis for a partial correlation for equilibrium constants in the critical region at elevated temperatures and pressures. This correlation consists of:

1. Estimated values for ideal equilibrium constants at temperatures to 1000°F. and pressures to 1000 lb. per sq. in. for materials boiling from —258° to 1000°F.
2. An approximate method for estimating convergence pressures.
3. The relations between the convergence pressure, the vapor pressure, and the pressure and value of the minimum equilibrium constants for less volatile components.

Ideal Equilibrium Constants

Fig. 8 is a plot of the equilibrium constants at 660°F. as determined experimentally in runs 1 through 5 on mixture A shown as open circles, and in runs 17, 18, and 19 on mixture B, shown as solid dots and reported in Table 9.

The extensive effect of the critical region on the values of the equilibrium values of Fig. 8 is apparent. From plots similar to Fig. 8, representing data taken at other temperatures, it has been possible to estimate the values for ideal equilibrium constants at 200 lb. per sq. in. abs. pressure over the temperature range 550° to 800°F. for the pentanes, hexanes, heptanes, and for components having normal boiling points up to about 725°F. By plotting these data as a function of boiling point as in Fig. 5, it is possible to extrapolate these estimated ideal equilibrium constants to boiling points as high as 925°F. and as low as the methane boiling point.

Fig. 9 gives the results of this procedure in the form of a series of ideal equilibrium constants at 200 lb. per sq. in. abs. pressure over the temperature range from about 50° to 1000°F. and for boiling points ranging from that of methane up to 925°F. The open circles indicate the ideal equilibrium constants as determined from plots of the experimental data given in Table 9 and shown in Fig. 8 for 660°F. The squares and solid lines represent values obtained from a study of all available data[2]. The dashed lines represent the extrapolated values.

In all cases the agreement between the values obtained from binary systems and natural gasoline for ethane through heptane is entirely consistent with the data derived in this investigation. The slightly lower extrapolated value for methane may or may not be of appreciable significance. It is known that the value for methane is influenced to a considerable degree by the character of the solvent material[20].

From the curves in Fig. 9 it is possible to prepare a cross plot of log K vs. boiling point at any temperature for 200 lb. per sq. in. abs., or to determine the points on a log K vs. log P plot similar to Fig. 8 at 200 lb. pressure for any desired temperature and for those components shown in Fig. 9 or for other components by means of the cross plot just suggested.

From points for 200 lb. for the different components at the desired temperature, a complete plot similar to Fig. 8 may be prepared by drawing the ideal equilibrium constants through the points in such a manner that the curve for the log K vs. pressure of each component is similar to the curve for butane at 300°F. except for a vertical displacement along lines of constant pressure. This can be readily accomplished by first locating the ideal equilibrium constants for butane, setting a divider to represent the vertical distance or the differences between log K at 200 lb. for any desired component and butane, and using this setting of the dividers to construct log K vs. log P for the desired components.

Convergence Pressures

Some knowledge of the convergence pressure corresponding to any temperature for a given system is essential for the estimation of equilibrium values within the critical region.

In the case of binary systems it has been demonstrated[1] that the convergence pressure at any given temperature is the pressure on the locus of the critical points of various mixtures of the binary components corresponding to the given temperature; in other words, it is the critical pressure of the binary mixture whose critical temperature is the temperature in question. It is not the critical pressure of the mixture in equilibrium.

In the case of complex mixtures the problem is more difficult. It has been suggested[9] that, if it were possible to express in terms of two arbitrary complex components the composition of the liquid and the vapor phases that exist in equilibrium, the characteristics of the complex mixture would take on the properties of a binary mixture to the extent that the equilibrium constants for each individual component would be determined by the temperature and pressure. Also it would be possible to estimate convergence pressures from the critical locus of various mixtures of the two arbitrary complex components as in binary systems.

An attempt made to verify the existence of such a relationship has met with only indifferent success.

Fig. 10 shows part of the envelope of the light naphtha, the furnace oil, and complex mixtures A and B that were prepared from these materials. The curve drawn through the squares represents the critical locus of various mixtures of the naphtha and furnace oil. The solid circles represent the critical locus of various mixtures of pentane and a complex mixture, F, of a composition such that one of the mixtures has the same composition as mixture B. The critical points were computed by the methods recommended by Smith and Watson[24].

The convergence pressure at 660°F. as indicated from the plot of experimental data in Fig. 8 is approximately 725 to 800 lb. for both mixtures A and B. So far as the curves of Fig. 8 are concerned, the convergence pressure at 660°F. for mixtures A and B might be determined from either the locus of the critical points computed for mixtures of the naphtha and furnace distillate, or from the locus of the critical points computed from mixtures of pentane and some other complex mixture that would produce compositions of mixtures A and B. These two loci are not identical; it is clear, therefore, that the results from such a procedure become indefinite, depending upon the choice of the component.

A fundamental characteristic of binary mixtures is that the critical points of all mixtures of the same two components determine a single curve. If this same condition is to be fulfilled in the case of the complex mixtures, it follows that the two arbitrary complex components must be determined in a definite manner so that a single locus for the convergence pressure is obtained.

For any specified mixture, a single locus for the convergence pressures may be obtained if this locus of convergence pressures is defined as the locus of the critical points of the equilibrium vapor and liquid obtained from an equilibrium vaporization of the

original complex mixture at its critical temperature but at a pressure less than its critical pressure. Computed critical points of equilibrium vapors and liquids obtained experimentally from the equilibrium vaporization of mixtures A and B at pressures below their critical pressures and at temperatures approximating their critical temperatures are also plotted in Fig. 10 as heavy dashed lines.

In Fig. 10 the convergence pressures determined from these last curves are approximately the same as those determined from the other two critical loci when in close approximation to the critical point of the complex mixture itself, but the difference approximates 10 to 15 percent of the total pressure at temperatures farther removed from the critical temperature of the original mixture.

The use of the critical locus as computed from two arbitrary components gives indefinite but approximately correct values for the convergence pressure in many cases, such as for temperatures close to the critical temperature of the complex mixtures. To obtain more consistent results, the convergence pressures may be estimated by determining the locus of the critical points of the vapors and liquids produced by equilibrium vaporization of the entire complex mixture at pressures somewhat less than its critical pressure and at temperatures close to its critical temperature. These convergence pressures are still unreliable in many cases, such as in crude oil-natural gas systems.

Minimum Value for Equilibrium Constants

The components present in the complex mixtures may be divided into two groups: (a) those components with values for the equilibrium constants never less than unity and (b) those components with values for the equilibrium constants which decrease to a minimum and then converge to unity at the convergence pressure, as the pressure is increased.

The former group, known as the more volatile components, when plotted as in Fig. 8 begin to depart from the ideal values at lower pressures for materials of lower boiling point. The second group, or the less volatile components, deviate from the ideal values and exhibit minimum values for the equilibrium constants, at lower pressures for components having higher boiling points.

Recently Gilliland[5] presented a correlation of the minimum values of equilibrium constants occurring in various binary systems, and suggested that the pressure at which this minimum value occurs in a diagram such as Fig. 10 is the arithmetic average of the convergence pressure and the vapor pressure of the components.

Fig. 11 is a plot similar to Gilliland's Fig. 10[5]; it includes data on additional binary mixtures and complex mixtures [4, 5, 8, 10, 11, 14, 21, 22, 23]. The ordinate is the ratio between the convergence pressure and the vapor pressure of the components at the temperature of the isothermal plot, or the ratio of the convergence pressure to the pressure at which the ideal equilibrium constant is unity.

Fig. 12 may be used to determine the pressure at which the equilibrium constant has a minimum value. The symbols in Fig. 12 have the same significance as in Fig. 11. The same ratio between the convergence pressure and the pressure at which the ideal equilibrium constant is unity is used as the vertical axis. The horizontal axis of Fig. 12 is the ratio between the pressure at which the equilibrium constant had its minimum value and the convergence pressure. The relations of Figs. 11 and 12 appear to be equally satisfactory for both binary and complex mixtures.

Conclusion

The ideal equilibrium constants, the correlation of minimum equilibrium constants, and the method suggested for estimating convergence pressures may be used to obtain consistent and reasonably accurate information concerning equilibrium vaporization of complex hydrocarbon mixtures at conditions which do not approach the critical region too closely. The use of the relations of Figs. 11 and 12 give substantially the same values for the equilibrium constants at pressures up to about one third the value of convergence pressure, even if the convergence pressure itself is in error by 25 or 30 percent. In many cases the critical point of the mixture in equilibrium may be used as a convergence pressure. In general, it is not necessary to determine with any degree of precision the convergence pressures unless the computations to be made are in the high-pressure region, close to the convergence pressure itself.

However, the importance of making changes in the equilibrium constants due to an approach to critical conditions cannot be overemphasized. The effect of a convergence pressure of 700 or 800 lb. is reflected in the values of the equilibrium constants for many mixtures at pressures as low as 150 or 200 lb. Furthermore, the effect of the convergence pressure is much greater in amount than is the usual difference between the ideal equilibrium constants and the values which may be computed from Raoult's law.

The relations outlined are fundamentally sound and can be considered reliable in case of all binary mixtures. They also appear to be a good approximation to the equilibrium relations between vapors and liquids of complex mixtures. The major difficulty is the correct estimation of the convergence pressure. For most engineering calculations, particularly where the working pressure is less than 50 percent of the estimated convergence pressure, satisfactory results can be obtained without the necessity of making careful calculation to determine the convergence pressure. In such cases the convergence pressure can be estimated with sufficient accuracy from the critical pressure of the mixture itself and from estimates of critical pressures of other similar mixtures.

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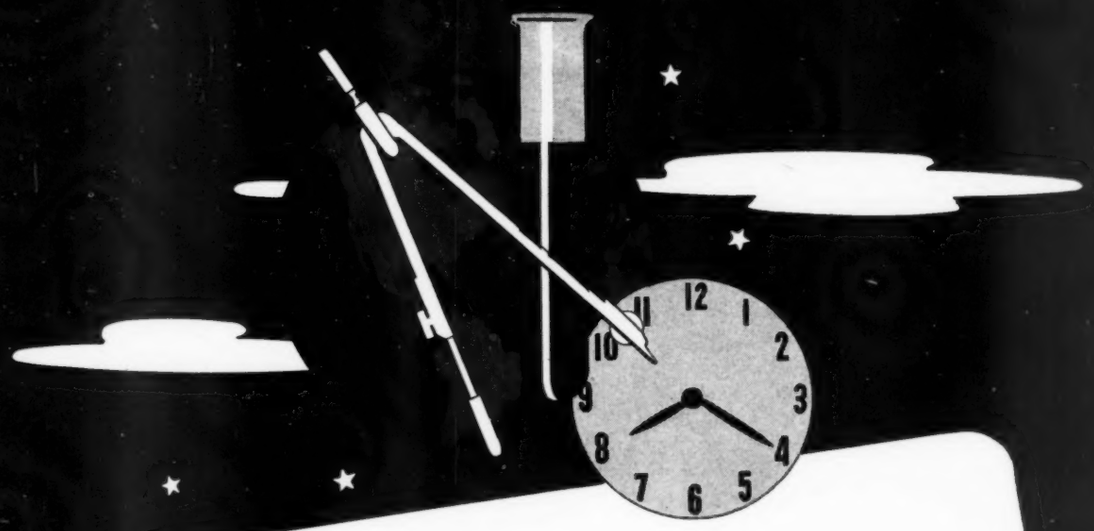

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Natural Gasoline Plant Layouts in 1942 *

By DON E. McFADDIN

Union Oil Company of California

FOUR primary factors to be kept foremost in mind when designing a layout for a natural gasoline plant are:

1. Safety.
2. Economy.
3. Efficiency.
4. Future expansion.

General trends in new layouts during the last ten years reflect more consideration to these four primary factors, with the result that there are now a number of examples of good layout design available for study. More specifically it is found that distances between the respective units or groups of units of new plants have been increased in order to gain safety and efficiency and to provide for future expansion. Also there is a definite trend toward utilizing the natural terrane to best advantage. In fact, it is generally agreed that the first step in designing a modern natural gasoline plant layout is to make an extensive study of the terrane, character of surrounding property, and prevailing winds pertaining to the proposed plant site. However, comprehensive technical formulas for converting the data of such a study into an optimum layout design are lacking. Therefore, in the final analysis, the decisions involved in designing a layout depend on experience, sound judgment and engineering ability. It is the purpose of this paper to stimulate the use of this engineering ability by reviewing present trends and opinions. With this in mind, questionnaires have been circulated to obtain personal opinions on the following:

1. Optimum distance between respective unit and property lines.
2. Use of concrete trenches for lines versus burying them, elevating them, or laying them on top of the ground.
3. Master control panels and instrument boards versus individual instruments and control valves placed at the respective units.

Distances

City and county ordinance now place limitations on minimum distances for plant layouts in most areas. These ordinances will not permit the building of congested plants in city areas such as have been built in certain localities in the past. A recent plant constructed on level terrane at Wilmington in the City of Los Angeles was designed to conform with the following:

1. Gasoline storage tanks and gasoline loading racks should be not less than 30 ft. from the property line.
2. Boilers, compressor plants, etc., should be not less than 20 ft. from such boundaries.
3. Compressor plants should be not less than 125 ft. from any drilling well.
4. Compressor plants should preferably be not less than 100 ft. from the distillation and absorption units and the gasoline storage tanks.
5. The boilers should preferably be on the windward side of the plant (with respect to prevailing winds) and not less than 100 ft. from the distillation and absorption units and on the opposite side of the plant from the gasoline storage tanks.
6. The gasoline loading rack should be located at least 100 ft. from any of the plant operating area.

The U. S. Department of Commerce published Bureau of Mines Technical Paper No. 462 entitled "Safety at Natural Gasoline Plants" by G. B. Shea. This publication gives primary consideration to hazardous vapors and the contour of the site in relation to the location of equipment. It is quoted as follows:

"The interest of safety and utility are best served in placing boilers, pumps, and compressors on one down flank of an elevated ridge; and absorber, distillation units and storage tanks on the other. Cooling towers should be preferably located on the crest of the hill. With this arrangement, all equipment is located so that no oil or gasoline can flow to the boilers."

This publication further states:

"Boilers should be set as far from the plant as practical and on the side away from dangerous hazards. This distance should not be less than 100 ft. Gasoline vapors travel long distances and many disastrous fires have been caused at gasoline plants by wind-blown vapors reaching the fires under nearby boilers. Another feature to be considered in laying out a site is to orient the plant with reference to the prevailing winds so that they will blow from the direction of the boilers toward the plant. This will prevent vapors that may escape accidentally or otherwise from drifting toward the ignition source. Fire stills should receive the same consideration that is given boilers. Placing fire stills near boilers is a safety precaution as well as a convenience."

Technical Paper 462 also gives a picture to illustrate a plant built on a ridge. However, this picture shows the boiler plant situated down hill from various cooling tower and other absorption plant units. This is contrary to the implications in the Government publication. Therefore, it should be emphasized again that boilers and compressor plants should not be situated at low spots with reference to the rest of the plant. The boiler and compressor plants are better situated near the crest of the ridge. It is desirable, from the standpoint of operating efficiency, that the cooling tower also be situated on a crest. Consequently, our ideal plant would have the boiler plant, compressor plant, and cooling tower all on the same ridge with safe distance between or, better still, the cooling tower and plant on one ridge and the boiler plant on another with a small ravine between. Quoting further from Technical Paper 462, "In addition to the arrangement of the plant proper, the location of the office, warehouse, and laboratory must be given consideration. These

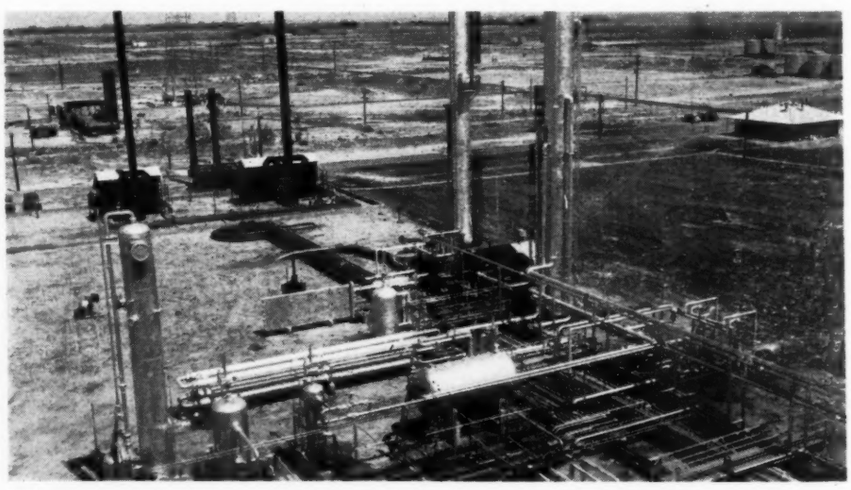

Fig. 1

*Presented before California Natural Gasoline Association, July 2, 1942.

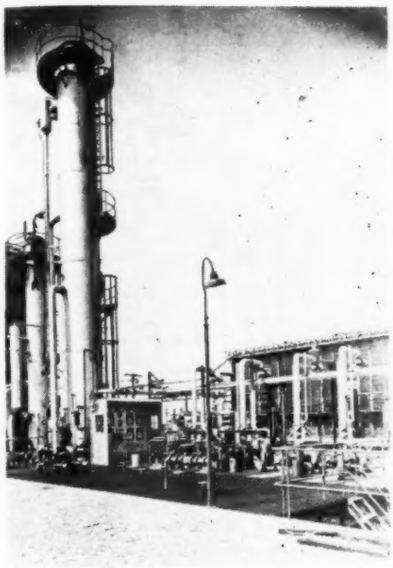

Fig. 2

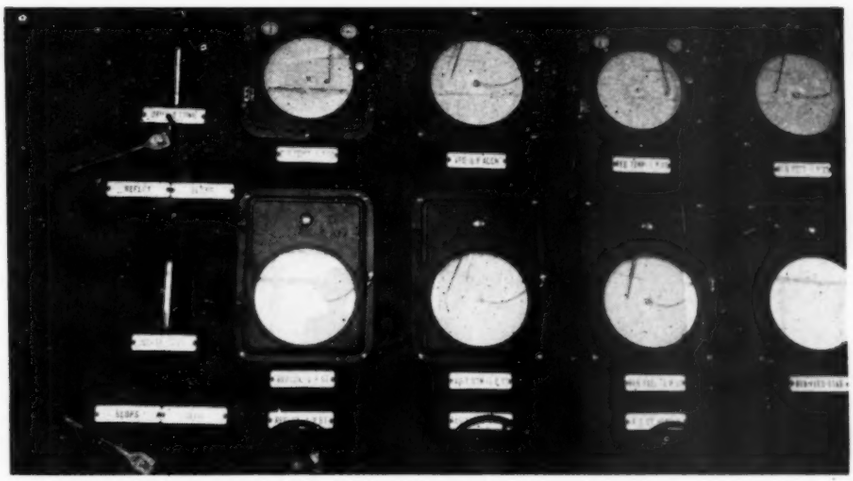

Fig. 3

buildings should be placed reasonably close to the plant but outside the danger zone and on the side opposite the plant storage. Likewise, they should be so located that it would not be necessary to drive or walk through the plant yard to reach them because of the danger inherent in the exhaust of cars and trucks and especially of smoking."

Table 1 summarizes the optimum distance between various units as indicated by the questionnaire data.

It is apparent, from Table 1, that there are wide differences of opinion on the preferable distances between the various units of a plant. This may indicate the futility of attempting to set fixed distances for layouts that would be acceptable to all. It may also indicate that the preferable distances are largely dependent on the various factors peculiar to each individual plant.

Installation of Lines

It was the tendency some ten years or more ago to bury all but steam and hot vapor lines. After much costly experience with corrosion and complications involving dead and forgotten lines and connections, the trend is now toward exposed lines.

It is apparent, from Table 2, that opinion favors elevating most steam, oil, and gasoline lines overhead, while placing gas lines on the top of the ground is preferred. The use of the concrete trench does not appear to be extensively favored. As to be expected, opinion favors burying only drainage and water lines.

Suction piping for centrifugal pumps is an item that has not received proper consideration in the past and numerous turns and dips have been a source of grief. By giving proper thought to the layout, the length of suction piping can be kept short and relatively free of sharp turns. In certain cases, such as the pumping of hot oil or gasoline, the fluid source, such as the still or stabilizer, may be advantageously elevated on a skirt. It may be desirable to keep the suction piping overhead and utilize overhead suction pumps. This design has found wide application in refinery layouts.

When lines are on top of the ground, steps and ramps must be provided for ready accessibility, as shown in Fig. 1. Concrete trenches with subway gratings provide a maximum of accessibility and convenience as shown by Fig. 2. The additional first cost of the concrete trenches and subway grating can often be justified for certain areas of the plant but usually not for an entire absorption plant in the field. Trenches and gratings are found more often in refineries than in field absorption plants because refineries are usually more crowded and must utilize the area over the lines for walkways and operating areas. Also the trenches are utilized for draining off leakage of heavy oil. Trenches and grating give a plant a finished appearance and if properly designed, with fire walls and drains, can be flushed with water and made to contribute to the cleanliness and safety of the plant. Unless they are properly designed, with ample vapor and liquid drainage and free from pockets, however, they may tend to accumulate explosive mixtures.

Some new absorption plants have followed the trend in refineries of providing a control house with a master control panel. Fig. 3 shows a front view of such a control panel with meters and hand operated control valves. However, Table 3 indicates that the master control panel in a centrally located control house has not found general acceptance in natural gasoline absorption plants. The questionnaire further indicated the average opinion that some 37 percent of the natural gasoline absorption plant instruments are preferably located individually

TABLE I

Preferable distances between various units of a natural gasoline absorption plant
Summary of questionnaire data

From	To (distances in ft.)					
	Street, highway or property Line	Gasoline storage	Gasoline rundown	Cooling tower	Stills	Absorbers
(1) Boilers and direct fired heaters						
Shortest distance reported	25	150	175	25	75	150
Longest distance reported	125	450	200	350	200	250
Average of distances reported	65	310	190	155	145	195
(2) Gas engines for pumps and compresses						
Shortest distance reported	20	50	75	20	25	25
Longest distance reported	75	400	150	200	150	150
Average of distances reported	49	235	110	63	75	75
(3) Street, highway, or property line						
Shortest distance reported	...	50	75	50	50	50
Longest distance reported	...	150	150	100	150	150
Average of distances reported	...	140	120	85	115	105

Notes: (1) Instructions were given to take roughly into consideration first cost, convenience of operation and safety.
(2) Level terrane is assumed.

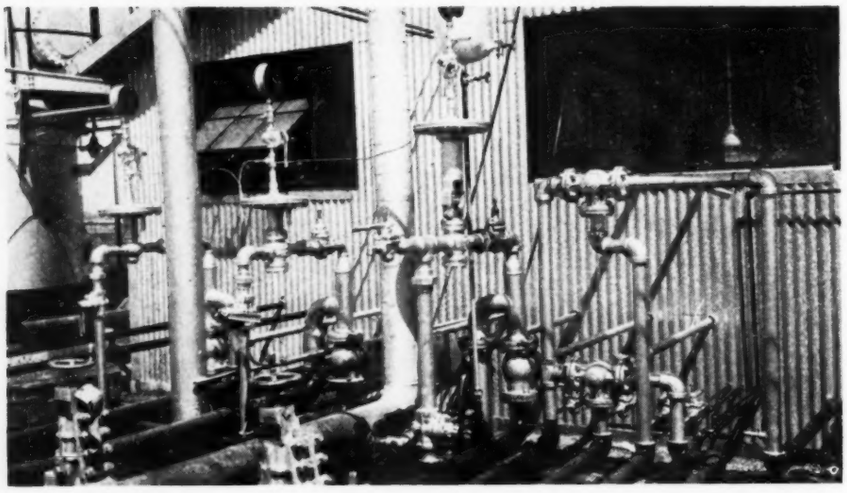

Fig. 4

throughout the plant, and 37 percent are indicated for open type panels. This leaves 26 percent for the master control panel.

In the present military emergency, a control house, from which the entire operation of the plant is apparent and can be largely controlled, is of definite value. It can be protected with sand bags or adobe bricks and used as a bomb shelter from which the plant can be operated during a blackout or actual raid. However, the control house requires considerable complication in the piping for main process streams as well as for the instruments in the control house and its first cost is very definitely greater than for instruments located throughout the plant adjacent to their respective units. Fig. 4 indicates the additional complexity of lines required for a central master control panel. It is surprising, however, to find that for the cases studied, the plant total first cost for a central control house with a master control panel amounts only to between one and two percent more than if the instruments and control valves are spread throughout the plant.

Fig. 2, in addition to the neatness and accessibility obtained with concrete trenches for piping, also shows a well designed open type master control and instrument panel serving several units of the plant.

One plan that has found favorable acceptance for some plants is to provide a small house without instruments, centrally located in the plant operating area. From this house, the operator can observe gauge glasses, pump operations, pressure gauges, etc. It can also be given bomb shelter protection. With this plan the operator is required to make occasional tours over the plant to adjust rates, temperatures, and pressures. In the case of an actual air raid, however, the plant would probably continue to operate satisfactorily for several hours without adjustments, if not damaged.

The control house may be effective in reducing operating labor. There is the belief, however, that this is false economy as it is desirable to have the absorption plant operator continually observing conditions throughout the entire plant. In order to explain the difference of the control house problem of the natural gasoline plant from that of a typical refinery plant, it should be remembered that space is usually more valuable in refineries, and refinery plants are usually considerably more compact. Also, personnel is organized on a different basis for refinery plant operations. The refinery plant operator is often expected to devote his entire attention to the control panel; while refinery shift foremen make routine inspections of the plant and a utility department has the responsibility of maintaining meters and instruments, also mechanics are usually available in case of mechanical trouble. The field absorption plant operator, however, often has the full responsibility of the entire plant and consequently should not spend his time at any one place.

Considerable progress has been made in plant layout during the last ten years and the modern absorption plant should excel the plant of ten years ago in safety and convenience of operation, economy of first cost and maintenance, and efficiency in the use of heat as well as the recovery of products. Undoubtedly the natural gasoline plant of ten years hence will be even better.

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TABLE 2

Preferable location of lines in natural gasoline absorption plants
Summary of questionnaire data

Location	Service					
	Drainage percent	Water percent	Oil percent	Gasoline percent	Gas percent	Steam percent
(1) Buried						
Lowest value reported	90	30	0	0	0	0
Highest value reported	100	100	70	10	50	0
Average of values reported	98	78	18	4	23	0
(2) In concrete trenches						
Lowest value reported	0	0	0	0	0	0
Highest value reported	0	20	75	50	25	0
Average of values reported	0	4	35	28	21	15
(3) On top of ground						
Lowest value reported	0	0	0	0	0	0
Highest value reported	0	30	30	25	90	10
Average of values reported	0	6	6	10	36	2
(4) Elevated overhead						
Lowest value reported	0	0	25	25	0	90
Highest value reported	10	40	90	90	75	100
Average of values reported	2	12	41	56	20	83

Notes: (1) Instructions were given to express preferences as percentages in each of the four classes of locations.
(2) Values in this table are percent.

TABLE 3

Control panels in natural gasoline absorption plants
Summary of questionnaire data

	Minimum percent reported	Maximum percent reported	Average of all percent values reported
(1) A master control panel in a single control house that can be steam heated, given full protection against the weather and can be blacked out	0	75	26
(2) Several open type panels strategically located in the plant	0	90	37
(3) Individual instruments conveniently located along walkways	10	100	37

Note: Values express preferences for percentage distribution between the three classes of meter installations. For example, one report indicated that 10 percent of all the plant instruments should be located individually along walkways, whereas another report indicated that 100 percent or all should be individually so located, and the average of all reports gave a percentage of 37 located individually.

P 773.44

Liquid Capacity of Bubble Cap Plates*

By

A. J. GOOD, M. H. HUTCHINSON, and W. C. ROUSSEAU

E. B. Badger and Sons Company

THE amount of liquid that can be handled by a bubble plate is a function of the driving force and the resistance to flow across the plate. The resistance to liquid flow is created by the bubbling caps in its path, and the necessary head across the caps to overcome this resistance appears as a kind of hydraulic gradient, called "liquid build-up" in this paper. Although reference to such a gradient or build-up has been made by Chillas and Weir,[2] Carey,[1] and others, little definite information concerning the variables that affect its magnitude has been published.

Some time ago it was found that the available information on entrainment, pressure drop through caps, downpipe capacity, etc., was not sufficient to permit the design of large towers or of smaller towers having high liquid loads. Studies on the operation of certain towers indicated low efficiencies that could be due only to highly irregular distribution of vapor and liquid caused by build-up of liquid above that allowed for in the design calculations.

In order to obtain information on flow of liquid across plates and the factors affecting distribution of liquid and vapor, work was carried out on the various types of bubble caps and plates in commercial use by this company. Data are for 3-in. diameter caps spaced with centers on 4¼-in. equilateral triangles. This cap is used primarily for vacuum towers where it is desirable to keep pressure drop at a minimum. Required liquid rates for this service are usually comparatively low and, as might be expected, liquid-carrying capacity for this type of cap is correspondingly low. This cap was chosen for initial presentation primarily because it has a relatively high build-up and the effect of variables is pronounced.

Stable plate operation is shown in Fig. 1. In general, the difficulties that arise from excessive build-up and result in bad distribution of vapor and liquid are illustrated in Figs. 2A and B and 3B. The build-up is such that some of the caps are not bubbling and others are badly overloaded with respect to vapor. In a large tower the area of blanked-off or inactive caps may shift from side to side; hence the term "unstable" has been applied to a plate on which some of the caps may be inactive. The degree of instability varies, depending upon relative vapor and liquid rates. The case shown in Fig. 3B is quite severe, with four out of twelve rows blanked off. Fig. 2B shows a less severe case with only one row blanked off. In a severe case, such as that of Fig. 3B, liquid may run down the chimneys of the upstream rows and thus bypass the plate. This can be serious, especially if the tower is of the cross-flow type with liquid flowing from side to side in opposite directions on alternate plates. In this case liquid running through the chimneys may essentially bypass two plates. Although it is possible to have virtually any unstable plate condition operate without liquid running down the chimneys by using caps having sufficient chimney overlap (Fig. 4), it is impossible with the usual designs of caps to have liquid flow down the chimneys when a plate is stable. Thus, a design which will guarantee stability will automatically guarantee that liquid will not flow down the chimneys.

Experimental Procedure

The construction of the experimental unit is illustrated by Fig. 5. Two removable rectangular plate sections approximately 5 ft. long and 2 ft. wide were used for this cap; one had chimneys 2 in. high, the other, 3½ in. high. Water, measured by an orifice, was pumped across the plate; air, measured by a Pitot tube or orifice and controlled by a damper on the suction of the blower, was blown into the space below the plate. Up to 12 rows of caps were used, each row suspended by trolley bars that were well above the plate to prevent interference with liquid flow. Adjustment of seal was made by a threaded pipe that served as part of the downpipe. Readings by means of gauge glasses were taken of the liquid height at downstream and upstream ends of the plate, and build-up was taken as the difference in these readings. It was important that the gauge glass taps be well away from the agitated mass; otherwise, disturbance would result in incorrect readings. At first a perforated plate was used just beneath the bubble plate to guarantee that all air entered the plate from below in one direction, but it was soon demonstrated that the screen had no detectable effect and it was eliminated.

Variables

Liquid rate is expressed as gallons per hour per linear foot of plate width normal to liquid flow. Often in the past liquid rate has been based on cross-sectional area instead of plate width. This method can lead to error, especially when some value of flow per sq. ft. is taken as a maximum. To illustrate the fallacy, let us use a maximum loading figure, as is often done, and apply it to 2- and 4-ft. diameter columns. The area of the latter would be four times the former, so the "allowable" flow would be assumed to be four times as great. A flow rate based on width or some average of diameter would be more nearly true since it would be directly proportional to the liquid velocity across the plate for constant depth. The plate width in these tests was uniform, but on a circular tower it is necessary to take an average. It is recommended that the arithmetic average of the width of the plate at the shortest and longest rows of caps be used with these charts.

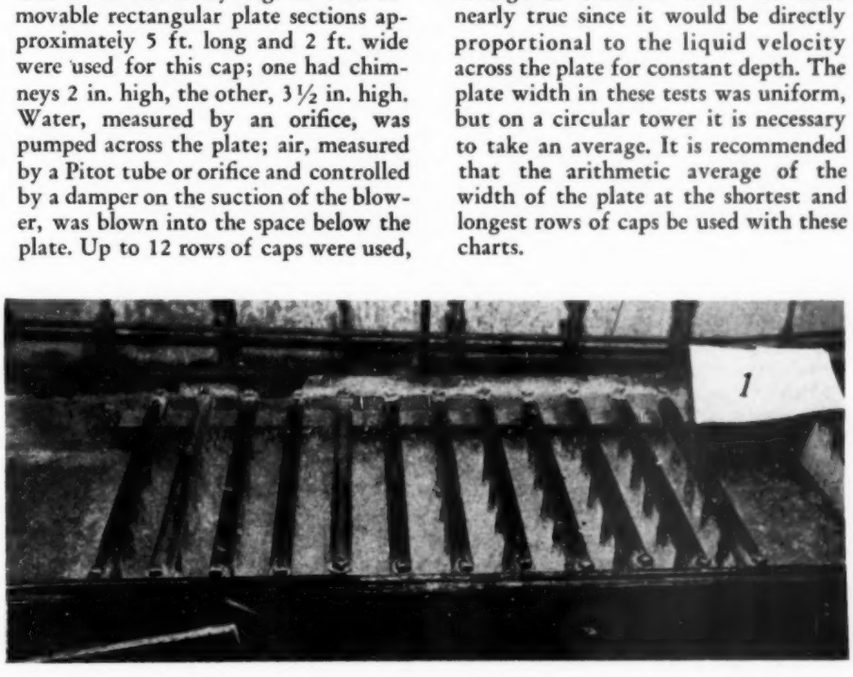

Fig. 1. Typical "stable" plate.
Skirt clearance = 1 in.
Liquid rate = 1000 gal. per hr./ft.
$S_{av} = 1$ *in.*
$v(\rho)^{0.5} = 0.81$

*Presented before American Chemical Society, Buffalo, New York, September 10, 1942, and published in *Industrial and Engineering Chemistry*, December, 1942.

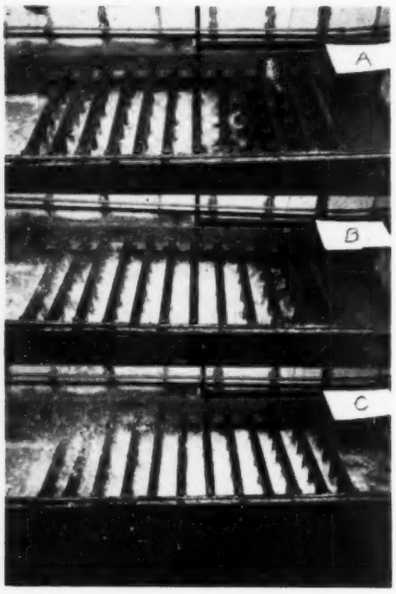

Fig. 2. Effect of vapor rate
Skirt clearance = 3/8 in.
Liquid rate = 1385 gal. per hr./ft.
S_{av} = 1 in.
A. $u(\rho)^{0.5} = 0.33$
B. $u(\rho)^{0.5} = 0.58$
C. $u(\rho)^{0.5} = 0.91$

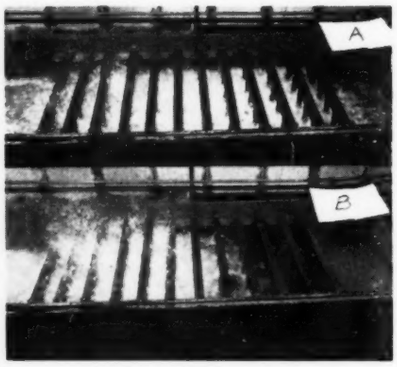

Fig. 3. Effect of liquid rate
Skirt clearance = 3/8 in.
S_{av} = 1 in.
$u(\rho)^{0.5} = 0.77$
A. Liquid rate = 1000 gal per hr./ft.
B. Liquid rate = 3000 gal per hr./ft.

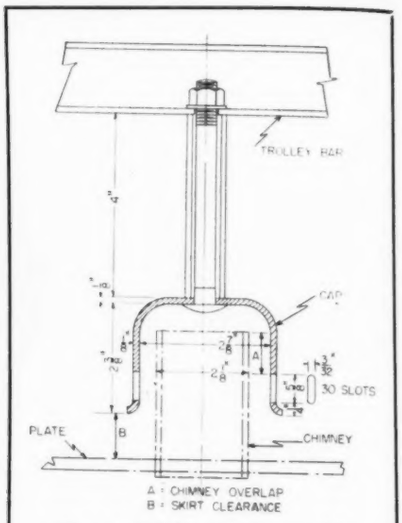

Fig. 4. Bubble cap assembly

Hydraulic gradient or build-up may be defined as the driving force, in terms of hydrostatic head, which must exist in order to overcome the resistance to flow of liquid across a bubbling plate or part of plate. On the laboratory plate, upstream and downstream calming sections were made free enough from turbulence and aeration to provide direct measurement of build-up across the bubbling portion of the plate in terms of head of clear water at atmospheric temperature.

Although the effect of vapor density on liquid build-up has not been determined in these investigations, all vapor rates are expressed as $u(\rho)^{0.5}$, where ρ is the density and u is the linear velocity of the vapor passing through the superficial cross section; in the experimental apparatus the area of the cross-section is taken as 9.25 sq. ft. This product is the simplified form of the term generally recommended for expressing maximum vapor load in a tower as determined by entrainment. It does not seem unreasonable to expect that vapor resistance to liquid flow should be a function of vapor "impact head," which is proportional to $u^2\rho$. As all runs were made using air, conversion of this factor to velocity above for the data presented can be made by multiplying by $1/(\rho)^{0.5}$ or by 3.6. Seal is used here as the depth of liquid, in terms of clear liquid, above the top of the slots. Fig. 6, which is an idealized

TABLE I

Original data with minimum seal constant at 1/4 in.

Run No.	Skirt clearance, in.	Liquid rate, gal./hr./ft.	$u(\rho)^{0.5}$	Δh, in. water	Δp, in. water	No. of rows bubbling
83A	3/8	500	0.36	0.30		12
			0.66	0.45	1.25	12
			0.98	0.58	1.65	12
			1.26	0.75	1.82	12
83B	3/8	1000	0.34	0.65	1.32	11
			0.67	0.90	1.52	12
			0.90	1.05	1.82	12
			1.27	1.35	2.28	12
83C	3/8	1385	0.35	1.10	1.39	8
			0.73	1.40	1.90	11
			1.08	1.65	2.25	12
			1.32	1.80	2.52	12
84A	1	500	0.35	0.19	0.87	12
			0.61	0.24	1.12	12
			0.95	0.30	1.55	12
			1.12	0.35	1.70	12
84B	1	1000	0.35	0.30	1.0	12
			0.56	0.40	1.2	12
			0.97	0.55	1.65	12
			1.23	0.75	2.0	12
84C	1	1385	0.37	0.60	1.1	11
			0.67	0.72	1.4	12
			1.06	0.95	1.9	12
			1.20	1.15	2.2	12
84D	1	2365	0.35	1.40		7
			0.64	1.59	1.75	9
			0.96	1.70	2.15	12
			1.2	1.85	2.35	12
84E	1	3365	0.35	1.85	1.7	5½
			0.60	2.15	2.15	7½
			1.02	2.60	2.65	11
			1.20	2.75	2.8	12
94A	1¾	500	0.36	0.05	0.7	12
			0.63	0.11	1.1	12
			0.95	0.11	1.45	12
			1.38	0.17	2.0	12
94B	1¾	1000	0.36	0.11	0.8	12
			0.58	0.13	1.0	12
			0.91	0.15	1.4	12
			1.25	0.25	1.85	12
94C	1¾	1385	0.43	0.23	0.95	12
			0.89	0.33	1.45	12
			1.3	0.46	2.0	12
94D	1¾	2365	0.40	0.69	1.15	11½
			0.80	0.78	1.55	12
			1.27	1.03	2.15	12
94E	1¾	3365	0.39	1.23	1.3	8½
			0.80	1.36	1.8	12
			1.20	1.53	2.25	12
97A	2½	500	0.37	0.03	0.75	12
			0.80	0.04	1.25	12
			1.25	0.05	1.8	12
97B	2½	1000	0.36	0.06	0.75	12
			0.91	0.10	1.25	12
			0.96	0.11	1.5	12
			1.19	0.15	1.8	12
97C	2½	1385	0.38	0.16	0.80	12
			0.82	0.20	1.35	12
			1.24	0.30	1.85	12
97D	2½	2365	0.36	0.40	0.95	12
			0.85	0.45	1.45	12
			1.24	0.56	1.9	12
97E	2½	3365	0.36	0.75	1.0	11
			0.87	0.83	1.7	12
			1.30	0.99	2.15	12

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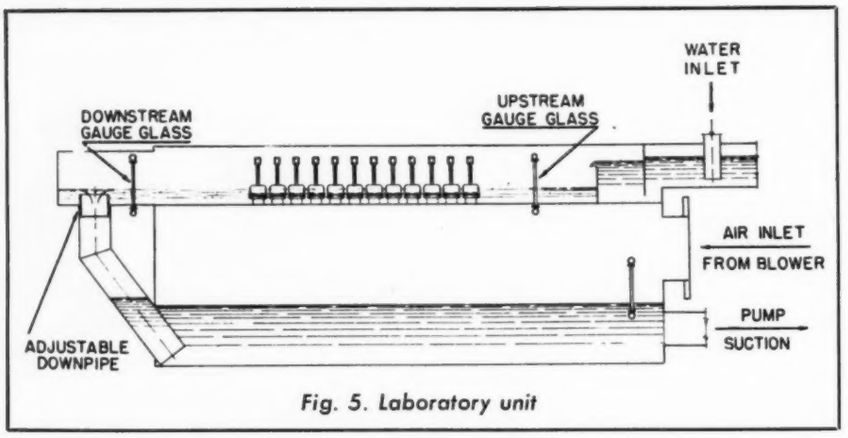


Fig. 5. Laboratory unit

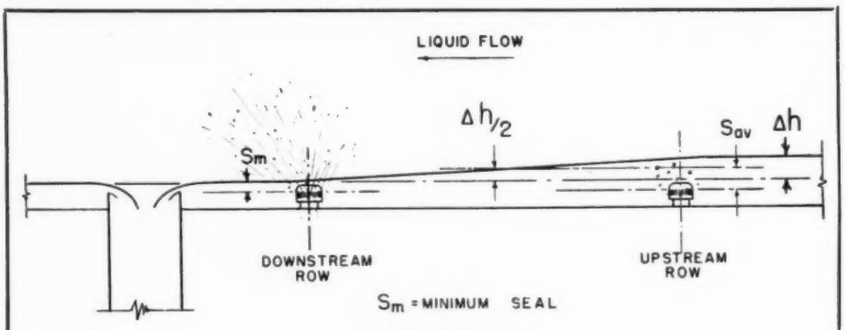


Fig. 6. Diagram of plate in operation

sketch, helps to illustrate the concept of seal and the relation of build-up to it. On an actual plate, liquid is in such a state of turbulence and aeration that minimum seal, S_m, is tangible only by reference to the depth of clear liquid at the downpipe, and average seal, S_{av}, cannot be visualized except by its mathematical definition.

Number of rows, as used in the build-up chart or capacity chart, refers to the number of rows of caps that lie across the path of liquid flow. In some cases of unusual types of flow this number can only be estimated.

The term "liquid capacity" means the maximum volume rate of liquid flow at which all upstream caps are active. If this rate is exceeded, caps become inactive as a result of too great liquid build-up.

Skirt clearance is the distance between the bottom of the cap and the plate. This distance is measured in inches. (Fig. 4).

Results

Beside liquid and vapor rates, the variables studied were seal and skirt clearance. Table 1 gives original laboratory data for a series of runs taken at constant minimum seal. Skirt clearances of ⅜, 1, 1¾, and 2½ in. were studied. Vapor rates were varied between zero and $u(\rho)^{0.5} = 1.6$, and liquid rates up to 3400 gallons per hour/foot were taken.

Typical plots of build-up, $\triangle h$, against vapor rate, $u(\rho)^{0.5}$, are shown in Fig. 7. Numerals beside points indicate the number of rows out of 12 that are not bubbling. Fig. 2 shows qualitatively the effect of an increase in vapor rate.

A comparison of curves at different seals indicates that $\triangle h$ is less at higher seals. This is especially noticeable at the lower skirt clearances where the percentage change in pool depth is greatest for a small change in seal. As minimum seal applies only to the downstream end of a plate because of build-up, some kind of average seal should be used in a correlation. A simple arithmetic average,

$$S_{av} = S_m + \frac{\triangle h}{2}$$

as illustrated by Fig. 6, was found to be a reasonably reliable expression of seal as it affects build-up, and another series of runs was made in which this average seal was kept constant as vapor rate was increased. Representative data for these average seal runs are given in Table 2. Some of these are shown by Fig. 8. The constant seal curves of $\triangle h$ vs. $u(\rho)^{0.5}$ are somewhat steeper than the corresponding curves for constant minimum seal.

The effect of liquid rate on build-up is shown in Fig. 9. This is a cross plot derived from plots of the original data by letting lines of constant vapor rate intersect the smoothed curves. Points enclosed in parentheses are for unstable regions. It is apparent that build-up is roughly proportional to liquid rate for rates up to about 1500 gallons per hour/foot. Above this rate the curves based on average seal swing upward, especially for lower seals. Fig. 3 shows

TABLE 2
Original data with average seal constant

Run No.	Skirt clearance, in.	Av. seal, in.	Liquid rate, gal./hr./ft.	$u(\rho)^{0.5}$	Δh, in. water	Δp, in. water	No. of rows bubbling
100A	⅜	2.0	1000	0.33	0.56	2.1	8½
100B				0.68	0.69	2.3	12
100D				1.31	0.88	2.7	12
101A	⅜	2.0	1385	0.34	0.77	2.2	8
101C				0.90	1.15	2.4	12
101D				1.23	1.20	2.7	12
102A	⅜	2.0	2365	0.92	2.06	2.7	8½
102B				1.20	2.33	2.95	12
102C				1.50	2.42	3.1	12
103A	⅜	2.0	3365	1.52	3.40	3.65	..
117A	1	½	500	0.32	0.26	1.04	12
				0.92	0.40	1.66	12
				1.52	0.66	2.29	12
118A	1	½	1000	0.31	0.36	0.95	11
				0.91	0.64	1.60	12
				1.52	1.21	2.40	12
119A	1	½	1385	0.30	0.63	1.10	11
				0.91	1.15	1.68	12
				1.53	1.83	2.46	12
117C	1	2	500	0.31	0.32	2.32	11
				0.92	0.31	2.72	12
				1.53	0.5	3.25	12
118C	1	2	1000	0.30	0.40	2.20	8
				0.93	0.55	2.69	12
				1.52	0.80	3.28	12
119C	1	2	1385	0.29	0.49	2.34	8
				0.92	0.71	2.76	12
				1.52	1.04	3.30	12
120C	1	2	1875	0.28	0.68	2.29	7
				0.93	1.00	2.74	12
				1.52	1.39	3.33	12
121C	1	2	2365	0.28	0.87	2.30	6
				0.92	1.35	2.76	11
				1.52	1.65	3.35	12
122C	1	2	3365	0.28	1.09	1.93	5
				0.92	2.04	2.65	9
				1.52	2.44	3.20	12

qualitatively the effect of an increase in liquid rate.

Fig. 10 shows that, for this type of cap in this arrangement, build-up may be considered as directly proportional to the number of rows across the path of the liquid. Data for this plot were taken by removing caps and plugging chimneys of four and eight downstream rows. Points for the vapor rates shown are taken from $\triangle h$ vs. $u(\rho)^{0.5}$ plots of original data and have been interpolated for a constant average seal of 1 in.

Fig. 11 is a condensed representation of all build-up data. Data taken at constant minimum seals were interpolated for constant average seals, and the best straight lines drawn to represent $\triangle h$ data up to 1500 gal. per hour/foot. Intersection of lines by the 1000-gal. abscissa gives the ordinate $\triangle h_1$ in Fig. 11, an averaged build-up based on 1000 gallons per hour/foot and 12 rows; the pronounced effect of skirt clearance on build-up is illustrated. By applying the proportionality shown below, this chart can be used for different numbers of rows and different liquid rates. For average seals of less than 1.5 in., however, the curves give values of Δh_1, which are too low if applied to liquid rates greater than 1500 gallons per hour/foot. The factor 7.14/N is included in the abscissa to permit a correction to laboratory conditions of a plate on which N, the total number of caps divided by the area upon which u is based, differs from the value of 7.14 used for these measurements. The following equation may then be used to estimate build-up from Fig. 11, subject to the limitations discussed earlier:

$$\Delta h = \Delta h_1 \left(\frac{\text{gal. per hr./ft.}}{1000}\right) \left(\frac{\text{No. of rows}}{12}\right) \quad . \quad . \quad . \quad . \quad (1)$$

As average seal is a function of Δh, trial and error procedure is necessary at the lower skirt clearances.

Although a series of runs with soapy water has confirmed the applicability of this build-up data to liquids of different foaming properties, the effects of liquid specific gravities and of viscosity have not been established. It is suggested, however, that the curves be considered as representing for other liquids an approximation of build-up in terms of a given pressure unit—e.g., inches of water (provided average seal is taken in terms of the existing specific gravity). This figure in inches of water

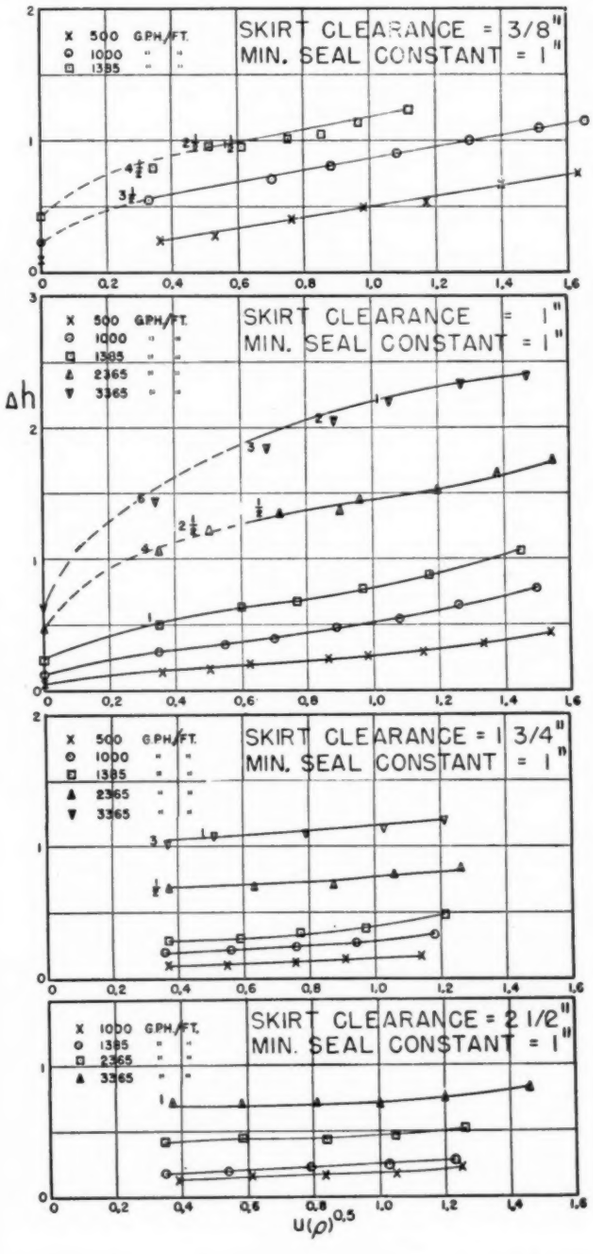
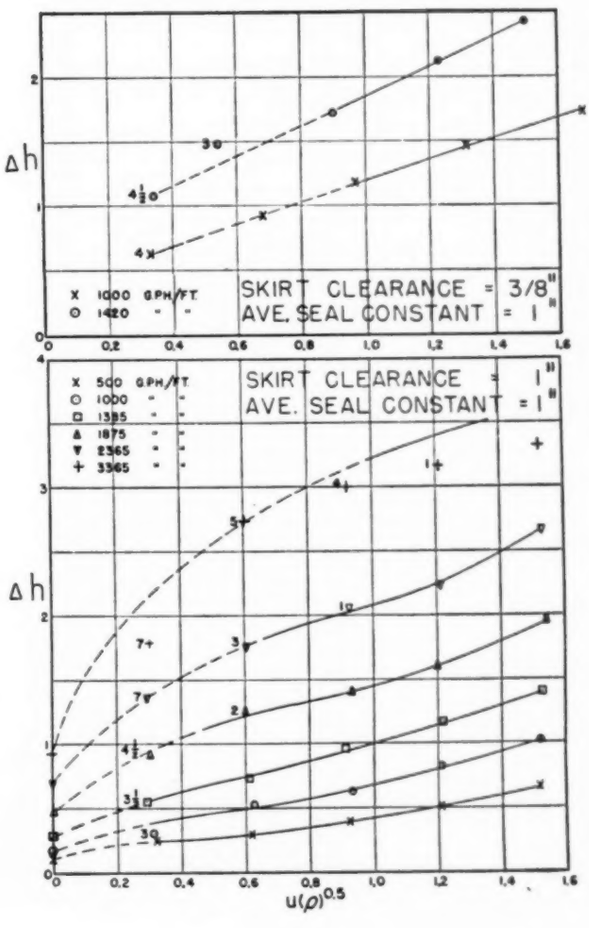
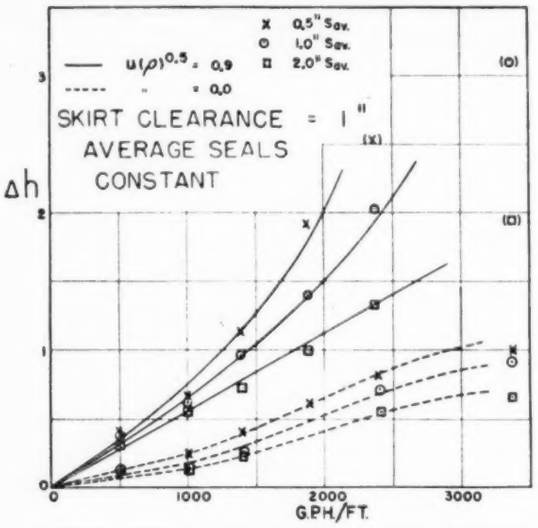

SKIRT CLEARANCE = 3/8"
MIN. SEAL CONSTANT = 1"
SKIRT CLEARANCE = 1"
MIN. SEAL CONSTANT = 1"
SKIRT CLEARANCE = 1 3/4"
MIN. SEAL CONSTANT = 1"
SKIRT CLEARANCE = 2 1/2"
MIN. SEAL CONSTANT = 1"
Δh
u(ρ)0.5

Fig. 7 (left). Original data for build-up vs. vapor rate at constant minimum seal

Fig. 8 (below). Original data for build-up vs. vapor rate at constant average seal





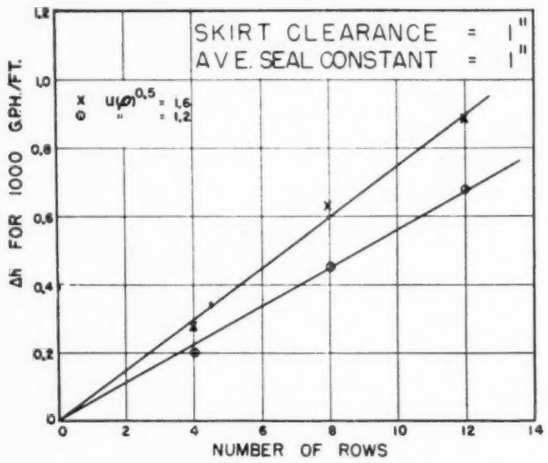


Fig. 9 (top). Effect of liquid rate on build-up

Fig. 10 (bottom). Effect of rows on build-up

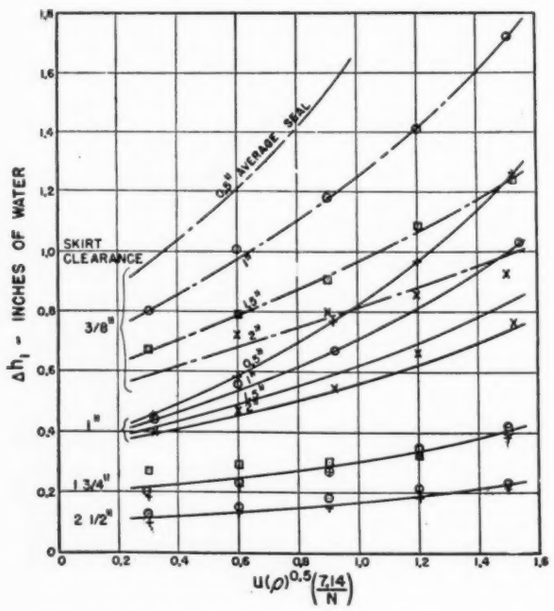
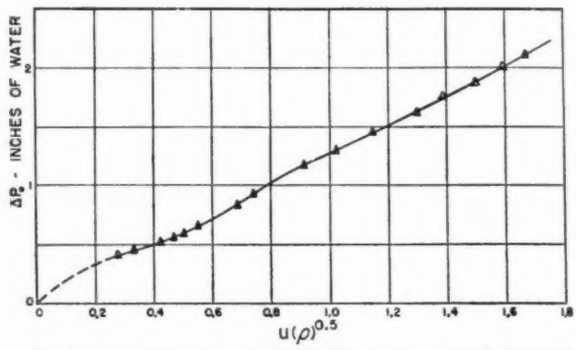
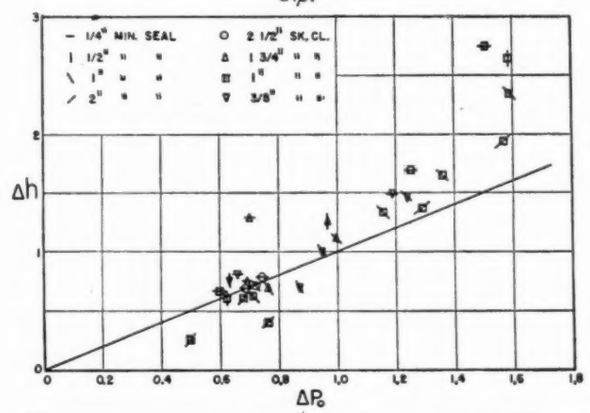


Fig. 11. Build-up chart, based on 12 rows and 1000 gal. per hour/foot

TABLE 3
Sample calculation of a capacity chart with skirt clearance and S_m of 1 in.

$u(\rho)^{0.5}$	Δp_0, in. water	Sav. in.	Δh_1, in. water	$\Delta p_0 \left[\frac{12\times1000}{\Delta h_1}\right]$
0.30	0.44	1.22	0.42	12,600
0.46	0.55	1.28	0.47	14,000
0.60	0.71	1.36	0.51	16,700
0.73	0.91	1.46	0.54	20,200





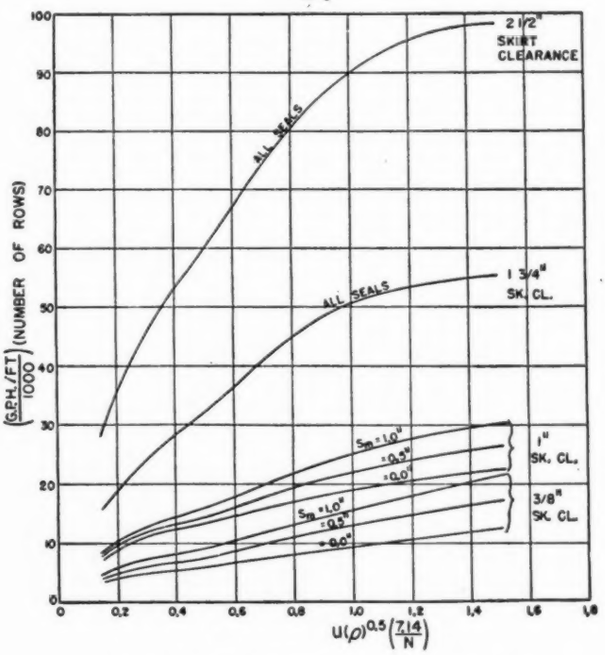


Fig. 12 (top). Pressure drop at zero seal

Fig. 13 (center). Build-up vs. $\triangle p_o$, from first run after all rows have become active

Fig. 14 (bottom). Liquid capacity chart

as computed by Equation (1) can be converted into inches of liquid flowing by dividing by its specific gravity.

Stability

For any given liquid rate across a plate there is a definite vapor rate, all else being constant, below which the plate is unstable. At high liquid rates this critical vapor rate is higher than at low liquid rates. As an approach to the relation between liquid and vapor rate, consider the simplified representation of a plate just barely stable, shown in Fig. 6. Let one cap in the last row downstream be indicated by A and one cap in the first row upstream by B. The bubbling at B is supposedly so slight that negligible vapor passes through, and therefore pressure drop of vapor, Δp_B, across the plate at B is made up of hydrostatic head alone, the sum of some function of S_m and of Δh. On the other hand, the total pressure drop across the plate at A, Δp_A, is made up largely of vapor losses (contraction, expansion, and friction) as well as hydrostatic head, the latter composed of some function of S_m and some function of slot opening.

It is obvious that $\Delta p_B = \Delta p_A$. If it can be assumed that the effect of S_m is the same at both A and B, then there should be a relation between Δh and the pressure drop at A up to the point of zero seal $(\Delta p_0)_A$, when Δh is expressed in the same pressure unit as Δp_0. The present data give both Δh and Δp_0 in inches of water. It would be difficult to determine $(\Delta p_0)_A$ or to estimate the exact relation of vapor rate at A to the over-all, or average vapor rate. However, pressure drop at zero seal—i.e., with liquid level (in terms of clear liquid at the down pipe) just equivalent to the top of the slots—has been measured over a wide range of vapor rates at a liquid rate so low that Δh was negligible. A plot of these values, Δp_0, is shown in Fig. 12. The data given here were taken at 1-in. skirt clearance with chimneys 2 in. high, but these agree with corresponding data for other skirt clearances.

No attempt was made to adjust vapor rate to the point of bare stability for each run. However, a rough check of the relation between Δh and Δp_0 close to the critical state can be shown by Fig. 13, in which Δh is plotted against Δp_0 for the first recorded vapor rate after all rows have started bubbling. The values of Δp_0 are read from the curve of Fig. 12 for a uniform plate, at corresponding values of average vapor rate entering the plate, and can be expected to apply to the plate with build-up only at the row where the actual vapor rate is equal to the average. In some cases the conditions are further from the critical than in others but a fair relationship exists, and at values of Δp_0 below 1 in. of water the best representation is the line of $\Delta h = \Delta p_0$. The conclusion can be drawn that a plate is stable provided Δp_0 based on average vapor rate is greater than Δh, both Δp_0 and Δh being expressed in the same pressure unit.

Since at higher values of Δp_0, most of the points fall above the line of $\Delta h = \Delta p_0$, it can be concluded that, as Δh increases, stability is possible even when Δp_0 is less than Δh. An explanation of the upward trend of the points may be found by considering Fig. 6 in connection with the foregoing analysis. Higher Δh means less uniform vapor distribution with a corresponding increase in the ratio $(\Delta p_0)_A/\Delta p_0$. It is significant that the points are independent of skirt clearance but tend to be lower for the higher values of minimum seal. This latter fact means that the assumption of equal effects of S_m at the extreme ends of the plate is not strictly true.

One point which must be stressed is that a plate is not always operating at high efficiency simply because it is stable. The build-up might be of such magnitude that too great a proportion of the vapor is passing through the downstream rows, and excessive entrainment might occur there. Fig. 2C shows a stable plate, and it is obvious that there is a marked difference in the proportion of vapor passing through each end of the plate.

Capacity Charts

The foregoing section demonstrated how probable stability can be predicted for a definite set of conditions. It involves individual determination of Δh and Δp_0. It is convenient to have a chart that will permit a quick check of liquid carrying capacity in order that unstable arrangements can be eliminated quickly from further consideration. Such a chart is shown in Fig. 14. The basis of this chart is the straight line of Fig. 13 and the premise that a plate is stable if Δh is not greater than Δp_0 taken at the corresponding value of $u(\rho)^{0.5}$ $(7.14/N)$. The further assumption is made that Δp_0 and Δh are functions of the same expression of vapor rate. The Δp_0 is represented fairly well by relating it to $u(\rho)^{0.5}$, especially at the higher vapor rates where the major component is pressure drop through the chimney and dry parts of the cap. At the lower vapor rates, pressure drop through the slots becomes a major component of Δp_0, and as slot pressure drop is a function of liquid specific gravity as well as vapor velocity and density (3), the values based on air and water used in the preparation of Fig. 14 are not applicable to all systems.

The ordinate is proportional to what might be called a "capacity product"—i.e., the product of rows times maximum liquid rate. The liquid rate below which all rows will be bubbling can easily be computed from the known values of vapor rate (corrected for the number of caps per sq. ft.), skirt clearance, and minimum seal. The more convenient minimum seal is used on the capacity chart, but in constructing the chart average seal is taken into consideration. This is made possible by the stipulation that for the condition of bare stability, $\Delta h = \Delta p_0$ and thus S_{av} is fixed for a given point. The procedure followed in making up the chart is demonstrated by Table 3. For a given vapor rate, Δp_0 is read from Fig. 12. By the relation $\Delta h = \Delta p_0$, S_{av} can be computed by adding $\Delta p_0/2$ to S_m. Knowing S_{av}, it is possible to interpolate for Δh_1 on Fig. 11, and by the proportionality expressed in Equation (1), the product of rows and liquid rate can be computed which will make $\Delta h = \Delta p_0$.

In using this capacity chart, it should be remembered that the build-up chart on which it is based applies to liquid rates under 1500 gal. per hour/foot and that erroneous conclusions may result at much higher liquid rates if the average seal is less than 1.5 in.

Example. An 8-ft. diameter tower is designed to absorb ethyl alcohol from a dilute mixture of air and alcohol vapor, using water as absorbing medium. Each plate is to have 350 caps with dimensions as shown in Fig. 4. The caps are to be placed on 4¼-in. equilateral centers, providing staggered flow, and to have a skirt clearance of 1 in. The following characteristics apply:

Vapor rate, $u(\rho)^{0.5}$	0.65
Total liquid load, gal. per hr.	7000
Plate width at short row of caps, ft.	6.5
Plate width at wide row of caps, ft.	8
Average plate width, ft.	7.25
Minimum seal, in.	1.0
Number of rows	19

$$\text{Actual liquid rate} = \frac{7000}{7.25} = 965 \text{ gal. per hr./ft.}$$

$$N = \frac{350}{(8)^2 \times 0.785} = 6.95$$

$$u(\rho)^{0.5}\left(\frac{7.14}{N}\right) = 0.65\left(\frac{7.14}{6.95}\right) = 0.67$$

Capacity. From Fig. 14 for skirt clearance = 1 in., $S_m = 1$ in., and $u(\rho)^{0.5}\left(\frac{7.14}{N}\right) = 0.67$:

$$\frac{(\text{gal. per hr./ft.})\,(\text{No. of rows})}{1000} = 19$$

$$\text{allowable rate} = \frac{19 \times 1000}{19} = 1000 \text{ gal. per hr./ft.}$$

As actual liquid rate is 965 gal. per hr./ft., the plate should be stable.

Build-up. First assume $S_{av} = 1.5$ in. From Fig. 11 for $S_{av} = 1.5$ in., skirt clearance = 1 in., and $u(\rho)^{0.5}\left(\frac{7.14}{N}\right) = 0.67$:

$\Delta h_1 = 0.51$ in.

$$\Delta h = 0.51\left(\frac{965}{1000}\right)\left(\frac{19}{12}\right) = 0.78 \text{ in.}$$

Check the original assumption of S_{av}:

$$S_{av} = 1 + \frac{0.78}{2} = 1.39 \text{ instead of } 1.5 \text{ in.}$$

Assume $S_{av} = 1.4$ in. From Fig. 11 for $S_{av} = 1.4$ in., skirt clearance = 1 in., and

$u(\rho)^{0.5}\left(\frac{7.14}{N}\right) = 0.67$:

$\Delta h_1 = 0.52$ in.

$$\Delta h = 0.52\left(\frac{965}{1000}\right)\left(\frac{19}{12}\right) = 0.80 \text{ in.}$$

$$S_{av} = 1 + \frac{0.80}{2} = 1.4 \text{ in.}$$

which checks the assumption. Therefore the build-up across the plate is 0.80 in. of water.

Conclusions

In order that liquid may flow across a bubble cap plate of the usual design, it is necessary that a hydrostatic head be set up between upstream and downstream ends of the plate. This differential of level can be so great that some upstream rows of caps are rendered inactive; all vapor is thus required to pass through the fewer caps which remain. Such an effect can lead to high pressure drop of vapor, bad entrainment, danger of flooding, and low efficiency.

Hydraulic gradient, or build-up, is shown to increase rapidly with liquid rate, expressed as volume per unit of time per unit of plate width. It is higher at low skirt clearance and low seal, and increases with increasing vapor rate. For the caps discussed in the present paper, build-up is proportional to the number of rows normal to liquid flow and, therefore, increases with tower diameter.

There is a definite relation between vapor rate and amount of liquid a plate can handle with all caps bubbling. If build-up is no greater than its equivalent in pressure drop up to zero seal, it can be expected that all caps will be active. As Δp_0 exceeds 1 in. of water, the ratio $\Delta h/\Delta p_0$ can be greater than unity with safety. This criterion makes possible the prediction of plate stability if the separate values of Δh and of Δp_0 (average for the plate) can be estimated.

It can be concluded that plate design should involve keeping build-up at a minimum, and that when high liquid rates are to be handled on a large-diameter plate, caps should be at a sufficient height above the plate. Also if vapor rate is so low that Δp_0 is low, it may be advantageous to use fewer caps on wider spacing. This has the twofold advantage of reducing resistance to liquid flow as well as increasing Δp_0.

The determination of stability should not be regarded as a substitute for other methods of establishing an optimum design. However, it is an important supplementary determination without which the usual calculations of pressure drop, entrainment, and plate spacing may have little value, since these usually assume a uniform plate.

It is obvious that the use of the capacity chart alone could lead to serious overloading of a tower from the point of view of pressure drop, entrainment, and efficiency, since the provision for stability alone often permits extremely high liquid rates at sufficiently high vapor rates. Even a stable plate can have such a high build-up at higher vapor rates that distribution of vapor is poor enough to cause bad entrainment and poor conditions for vapor-liquid contact.

Acknowledgments

The authors wish to express their indebtedness to W. A. Peters, Jr., of E. B. Badger and Sons Company, for his suggestions during the progress of the work reported in this paper.

Nomenclature

- Δh = build-up or hydraulic gradient, in. of water
- N = number of caps per sq. ft. of area upon which u is based (N = 7.14 for exptl. plate)
- Δp = total pressure drop through plate, in. of water
- Δp_0 = pressure drop up to zero seal or total pressure drop corrected for head of liquid above top of slots, based on average vapor rate through caps, in. of water
- S_m = minimum seal, difference between level of clear liquid at downpipe and level of top of slots, in.
- S_{av} = average seal, defined as $S_m + \Delta h/2$ in which Δh is expressed in inches of the liquid flowing, in.
- u = linear velocity of vapor based on superficial cross section of tower, ft./sec.
- ρ = density of vapor, lb./cu. ft.

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2. R. B. Chillas and H. M. Weir., *Trans. Am. Inst. Chem. Engrs.*, 22, 79 (1929).
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☆ ☆ ☆

Test Engine Saves Research Operating Time

Development of a new test engine for pre-evaluating heavy-duty Diesel lubricants has resulted in cutting test operating periods to 24 hours from 480, the Diesel Engine and Fuels and Lubricants Meeting of the Society of Automotive Engineers at Cleveland, Ohio, was told recently.

The report came from H. L. Moir, W. J. Backoff, and N. D. Williams, of The Pure Oil Company, Chicago, who said a single-cylinder Fairbanks-Morse Diesel engine has become a valuable research tool giving in 24 hours data correlating with those developed in 36-hour Chevrolet and 480-hour Caterpillar tests.

They said that correlation of ring-sticking with temperature rise in the piston ring area has been successful for about 40 percent of the heavy-duty oils evaluated, and that piston-cleanliness ratings afford helpful supplementary data. Describing test procedure, including change to a cast-iron piston, they reported loss in power output was found to be more sensitive to sluggish ring action or ring-sticking than to increased piston temperatures. Variations in ring-sticking time for each type of lubricant are ascribed to differences in degrees of refining and sources of crude.

SAE 30 oils of the Gulf Coast type were reported to prolong ring-sticking time to 17½ to 20 hours, as compared with 8½-10 hours for Mid-Continent and 4½-9 hours for Pennsylvania, but produced extremely dirty pistons, badly stuck rings, and overall engine sludge so difficult to remove that cleanliness had to be established as another characteristic to be considered in evaluating and producing heavy-duty type lubricants.

The Reciprocating Steam Pump in the Natural Gasoline Plant*

By
H. P. HENDERSON
Worthington Pump and Machinery Corporation

IN considering the reciprocating steam pump and its particular application to the problems of transferring water, oil, and the lighter liquid hydrocarbons through the natural gasoline plant, it will be well to review the various types and forms of this reliable piece of equipment.

Duplex pumps are those having two liquid cylinders side-by-side whereas the singles or "simplexes" are those in which only one cylinder is employed in each unit.

The steam valves are controlled by the motion of the piston rods, which perform the function of transmitting the power from the steam cylinder to the liquid cylinder. These steam valves are of two general types: namely, the "D" slide valve (Fig. 1-a) and the piston valve (Fig. 1-b). The slide valve is suitable for most steam conditions encountered in natural gasoline plants and elsewhere provided the total steam temperature is 450°F. or lower. When total temperatures range between 450° and 550°F. the piston steam valve is recommended because of its better lubrication, longer life, and freedom from warpage under superheat.

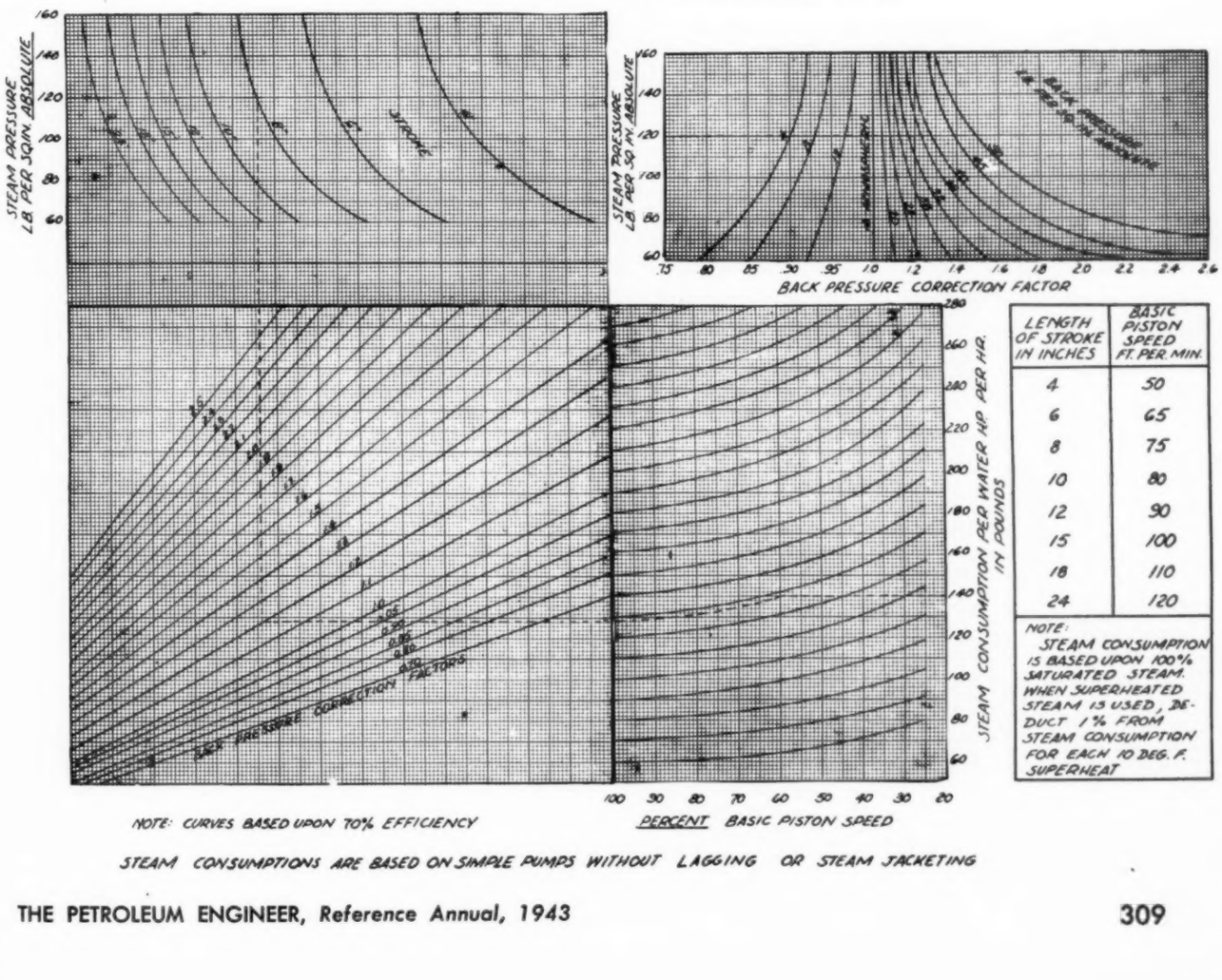
There are many types of liquid ends but there are only three of these that are suitable for use in the natural gasoline plant. One of these is the time-honored cap-and-valve plate design, Fig. 2a, and another the turret pattern, Fig. 2b, which have been used since the early days of gasoline plants for all services. Now, however, there is a better design for the lighter products—the side pot pattern shown in Fig. 3. The cap-and-valve-plate and turret patterns are now used chiefly for cooling water, absorption oil, and low vapor-pressure products.

Close-clearance pumps are well-designed side pot pumps in which the clearance spaces have been reduced to the lowest possible value. Fig. 4 shows one close-clearance side pot design called the Hivol. Compare this with Fig. 3 and you will see that the spaces which in the conventional side pot pump are open to the liquid are in the design of Fig. 4 eliminated to as great an extent as possible. Convention has been discarded and compressor practice followed.

This unconventional pump has a clearance volume of only 16 to 20 percent whereas the cap-and-valve-plate design has a clearance volume of between 125 and 200 percent. The close-clearance type pumps were tested as dry vacuum pumps and air compressors with remarkable results. Cylinders were

*Presented before California Natural Gasoline Association, April, 1943.

Steam consumption chart—duplex direct-acting pumps


STEAM PRESSURE LB PER SQIN. ABSOLUTE
SUPERHEAT
BACK PRESSURE CORRECTION FACTOR
STEAM CONSUMPTION PER WATER HP PER HR. IN POUNDS
PERCENT BASIC PISTON SPEED
NOTE: CURVES BASED UPON 70% EFFICIENCY
STEAM CONSUMPTIONS ARE BASED ON SIMPLE PUMPS WITHOUT LAGGING OR STEAM JACKETING

LENGTH OF STROKE IN INCHES	BASIC PISTON SPEED FT. PER MIN.
4	50
6	65
8	75
10	80
12	90
15	100
18	110
24	120

NOTE: STEAM CONSUMPTION IS BASED UPON 100% SATURATED STEAM. WHEN SUPERHEATED STEAM IS USED, DEDUCT 1% FROM STEAM CONSUMPTION FOR EACH 10 DEG. F. SUPERHEAT

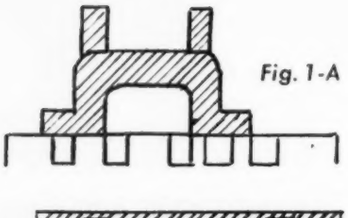


Fig. 1-A

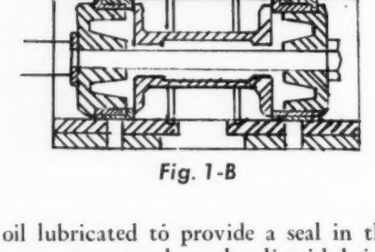


Fig. 1-B

oil lubricated to provide a seal in the same manner that the liquid being pumped normally seals the piston. As vacuum pumps the pressure obtained was reduced to from 3.7 in. of mercury absolute for the lowest vacuum and to 1.25 in. mercury absolute for the highest vacuum! Similarly, as air compressors, pressures could be maintained between 135 and 225 lb. per sq. in. gauge.

The significance of these tests will be discussed later in this paper.

Valves in the liquid end of a steam pump are as varied in design as milady's hats. To discuss the relative merits of the various makes or forms of valves has no place here and we therefore will confine our remarks to the basic requirements and functions of liquid valves. The two basic types are the disk and the guided types. Both have some points in common and these will be examined first. Neither disk nor guided type valve should be allowed to lift higher than ⅛ in. per in. of diameter or slamming and clatter will result, which is not only annoying but will lead to untimely wear and destruction. This is an old rule-of-thumb based upon experience and entirely satisfactory.

Let us now examine the losses or pressure drop through a valve and the pressure required to get it open.

In Fig. 5 let:

A=the nominal diameter of valve,
A=the area of diameter A,
B=the inside diameter of the valve,
B=the inside area of the valve,
S=the spring force in lb.,
W=the weight of the valve,
Pa=the pressure on A, lb. per sq. in.,
Pb=the pressure on B, lb. per sq. in.

With the valve closed, the force necessary to open the valve is:

$$P_B \times \mathbf{B} = P_A \times \mathbf{A} + S + W \quad . \quad . \quad (1)$$

$$P_B = \frac{P_A \times \mathbf{A} + S + W}{\mathbf{B}} \quad . \quad . \quad . \quad (2)$$

$P_B - P_A$ = opening differential or pressure required to get the valve open . . . . . (3)

On a conventional valve such as used in a Worthington 6 by 4 by 6 duplex steam pump, we find the following:

A=3.31 and **A**=8.19 sq. in. (XX),
B=2.15/16 and **B**=6.06 sq. in. (XX),
Sc=3.25 lb. (valve closed),
So=5.87 lb. (valve open),
W=0.5 lb., and
$P_B - P_A$ becomes (0.35 P_A+0.62) lb. per sq. in.
(XX—allowing for the guard hole.)

Thus we see that the pressure differential to open the valve is affected very slightly by the spring pressure and the weight of the valve, and to a marked degree by the width of the seat.

If this was a suction valve with boiler feed coming to it at 210°F. and with a net positive head measured at the valve seat of 15 ft., would the valve open without the water in the clearance spaces of the pump flashing? Let's see.

Vapor pressure of 210°F. water is 14.13 lb. per sq. in. abs.

15 ft. of water at 210°F. is equivalent to 6.2 lb. per sq. in.

Total absolute pressure at underside of valve is therefore 20.33 lb. per sq. in. abs. The pressure drop is 5.63 lb. and pressure inside the cylinder is 14.7 lb. abs. This is greater than the vapor pressure of the liquid and there should be no vaporization.

As soon as the valve is open area **A** equals area **B**. The correct lift of the valve in question would be ⅛ in. × 3.31 in. or 13/32 in. maximum. The clear area through the seat of this valve is 5.03 sq. in., and with 13/32 in. lift, the peripheral area is 4.22 sq. in.

When flow starts through the valve, the valve flow loss must be added to formula (2). This expression is derived as follows:

$$h(\text{ft.}) = \frac{V^2}{2g}$$

When V is the velocity through the system in ft. per sec. Assuming a discharge coefficient of 0.8 and converting to lb. per sq. in., we have:

$$\frac{V^2 \times \text{sp. gr.}}{2 \times 32.2 \times .8 \times 2.31} \text{ or } \frac{V^2 \times \text{sp. gr.}}{119}$$

Our formula then becomes:

$$P_B = P_A + \frac{So + W}{\mathbf{A}} + \frac{V^2 \times \text{sp. gr.}}{119} \quad . \quad . \quad (4)$$

For simple calculation, you may use the following formula to calculate the velocity through the valves:

$$V = \frac{0.64 \times \text{gal. per min.}}{\text{Net area} \times \text{no. valves per function per section}} \quad . \quad . \quad . \quad . \quad (5)$$

Thus, if the pump in question was handling 35 gal. per min., the valve loss is:

$$\frac{(5.31)^2 \times 0.96}{119} = 0.18 \text{ lb. per sq. in.}$$

This is for all practical purposes a negligible quantity.

The area of the suction valves relative to the piston area is a rather widely varying figure and depends upon the type of liquid end, its size and long-

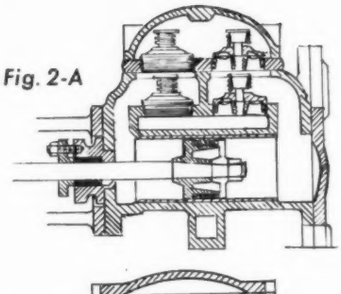


Fig. 2-A

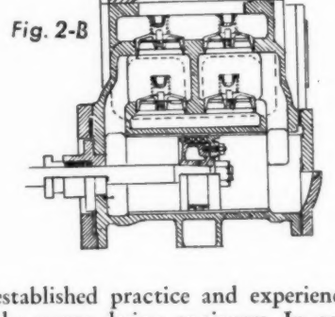


Fig. 2-B

established practice and experience of the pump design engineers. In general the cap-and-valve plate and turret pattern pumps will have valve area ratios ranging from 25 to 30 percent of the piston area. Pot valve and special close clearance design pumps will have valve area ratios ranging from 35 to approximately 50 percent on the very largest pumps. The highest percentages are recommended for viscous liquids encountered in refinery work but are often used in natural gasoline plants for high capacity work.

Reasonable speeds must be maintained on steam pumps if good, reliable service is to be obtained.

What constitutes "reasonable speed" is a point of considerable controversy. Some pumps are treated as though their operators felt that any speed was all right provided the steam valve motion did not come apart or the pistons knock the heads out of the pump. Such operation is distinctly bad because it leads to short life of not only pumps but usually to exchangers, piping, controls, etc., as well. Hydraulic shock or water hammer is usually set up and this may be destructive to equipment beyond the pump.

Reasonable speed is usually best determined by liquid valve and cylinder performance. Valve and cylinder performance are dependent upon the characteristics of the material being handled, the intake pressure and equilibrium conditions, and the intake piping. A pump may operate beautifully at a speed of 20 r.p.m. handling propane with a valve velocity of 100 ft. per min. and with the liquid cylinder filling completely each stroke. If the pump is speeded up to 30 r.p.m., the result may be lack of filling of the

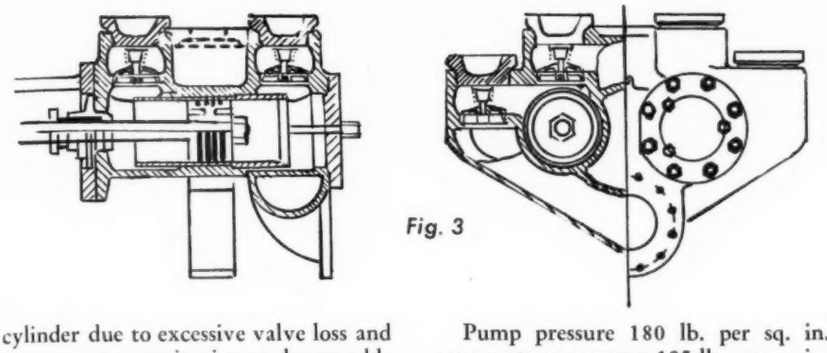


Fig. 3

cylinder due to excessive valve loss and consequent vaporization or due to added intake line velocity causing additional line losses which will cause flashing upon opening the suction valves or other similar causes. Yet with changed intake conditions the same pump may handle the increased quantity of the same liquid with ease as before.

The designers and operators of pumping systems must keep constantly in mind that there is no such thing as "suction." The pump, whether it be positive displacement or centrifugal, can force the liquid out but some external force such as atmospheric or tank pressure and gravity must cause the liquid to force open any line check valves, control valves, or pump valves and flow into the pump.

Generally speaking, pumps handling water and oils with viscosities under 250 S.S.U. can be operated at speeds as follows:

6-in. stroke, 45 ft. per min.
10-in. stroke, 63 ft. per min.
12-in. stroke, 70 ft. per min.
18- and 24-in. stroke, 90 ft. per min.

For volatile products these may have to be reduced 10 to 50 percent depending on intake conditions and valve velocities.

Liquid valve velocities in the order of 90 to 150 ft. per min. will usually be found satisfactory for volatile liquids whereas these velocities may be run up to as high as 250 ft. per min. or even more for handling very light oils and cold water.

Capacities and sizes of pumps may be quickly determined if one will remember a few simple facts and keep in mind the piston speeds given earlier in this paper. For simplicity remember that the following cylinders, 1 ft. long, have the following capacities:

3½ in.	½ gal.	7 in.	2 gal.
6 in.	1½ gal.	11 in.	5 gal.

Select a suitable size and divide into the capacity to be handled. If it falls within the range of speeds for a reasonable liquid cylinder size, then select a suitable steam cylinder size from the ratio of the steam pressure and liquid pressure with about 70 percent pump efficiency.

Example:

Desired—pump for 45 gal. per min. cold absorption oil.

Pump pressure 180 lb. per sq. in. gauge, steam pressure 125 lb. per sq. in. gauge, atmospheric exhaust.

Try—3½-in. pump, 6-in. stroke.

$\frac{1}{2} \times 45 = 22\frac{1}{2}$ gal. per min. If the pump is a duplex, the selection is good for 45 gal. per min. The nearest standard size is a 6 by 4 by 6.

Pump is large enough as selected.

Pump mechanical efficiencies will vary with size of pump, type packing, amount of load or pressure, tightness of rod packing, and general condition of wear. Units in good condition with new, well broken-in packing, on rated pressure will range from 50 percent for a 3-in. stroke pump through 65 percent for a 6-in. stroke, 78 percent for a 12-in. to 85 percent for 24-in. stroke. For practical purposes a figure of 70 percent is usually used for calculations.

$\left(\frac{6}{4}\right)^2 \times 0.7 \times 125 =$ operating liquid pressure or in this case 197 lb. per sq. in.

The steam consumption of a steam pump may be approximated quite readily as follows:

Calculate the displacement of the steam end in cu. ft. per hour. Also calculate (or measure) the actual steam pressure in the valve chest, taking into account pump mechanical efficiency and cylinder ratio. Multiply the calculated displacement by the density of the steam at the pressure and estimated quality. Increase this result by 15 percent to allow for the steam in the clearance spaces of the cylinder. If the pump is a simplex, increase this result by 75 percent to allow for condensation, stuffingbox loss, etc. If it is a duplex pump, however, increase by 90 to 100 percent depending upon smoothness of operation. The rougher running, short stroking pump uses more steam. The chart gives these steam consumptions very readily and is self-explanatory except that the results may be reduced by 10 percent for simplex pumps.

The close-clearance simplex pump is finding very wide application in the natural gasoline industry because these pumps can make up for bad suction conditions and still deliver the required amount of liquid. It is often necessary to install a pump in an existing plant to take its feed from a tank located without sufficient head. This usually results in gassing to the extent that a pump having vacuum pump and gas compressor characteristics must be used if any liquid is to be delivered. As the close-clearance pumps, as outlined earlier in this paper, do have compressor characteristics and as other pumps with greater clearances would gas bind, then in these cases the close-clearance pump must be used.

Plant engineers and designers should not, but sometimes do, take advantage of the characteristics of close-clearance pumps and locate supply tanks so low that even close-clearance pumps have no chance to give the service for which they were designed with the more serious results of bottlenecks in the plant.

Notwithstanding the widespread use of direct-acting pumps of both single and duplex types there still seems to be some confusion with regard to the comparative merits of the two kinds of construction. Each type has its advantages and its staunch supporters and a broad survey of the field would properly disclose the fact that in the matter of preference of one over the other opinion is about evenly divided.

The duplex pump is an extremely simple machine and its operation is easily understood by the most inexperienced engineer. It will stand an astonishing amount of abuse and will always run—in some sort of way—even when in the most wretched condition, although the amount of water pumped may be very much below rating and the steam wasted in driving it, an ap-

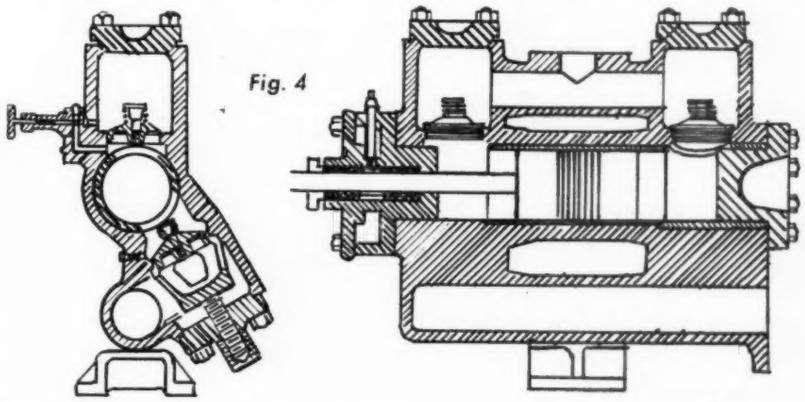


Fig. 4

palling amount—but it will run. Then, too, in case of total collapse it is usually easy for an attendant to tinker up the troubles and begin pumping again.

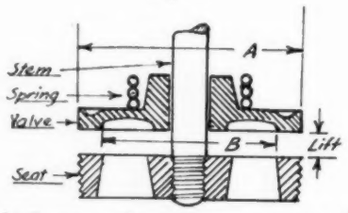
The water flow, from a duplex pump is smooth and free from fluctuation. Furthermore, the first-cost is usually a little less than that of a simplex pump of like capacity. On the other hand there are practically two pumps with all their operating parts which are needed to do the work of one.

An undesirable feature of the duplex pump is its tendency to short stroke, on account of unequal friction in the working parts of the two sides, due to the difficulty of packing the stuffing-boxes and pistons of both sides equally tight. This not only decreases the water discharge but increases in an equal degree the steam clearances, which means steam waste.

The simplex pump is a machine somewhat more refined in construction than the duplex pump yet consisting of but few parts and when all is told is a very simple affair requiring but ordinary attention—as little as an engineer would give to the humblest piece of his equipment. In comparison with its duplex relative, it has certain features in its favor, some of which are as follows:

It occupies less space—has fewer wearing parts—but half the number of stuffingboxes, pistons, and joints to pack and keep in order—makes full stroke at all times—will not short stroke under any running conditions,

Fig. 5



which means less clearance space that must be filled with steam and a saving that may be from 10 to 30 percent in steam consumption—has less steam cylinder condensation—is much better adapted for handling hot water, gases, mixtures of liquids, and propane or any service where liquid cylinder may not entirely fill with liquid at each stroke.

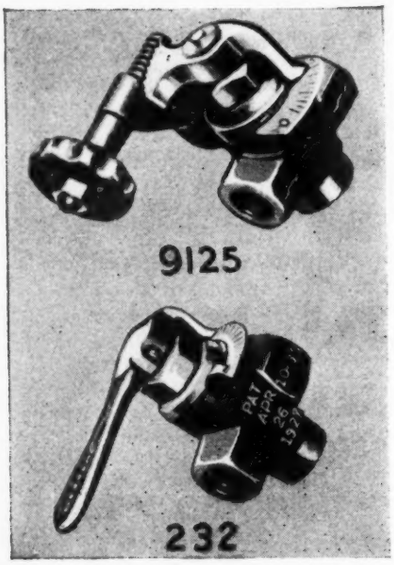
Conservative figures of a comparison of the steam consumption of the two types of pumps show that duplex pumps in the best of running conditions use from 10 to 30 percent more steam than simplex pumps of equivalent capacity and from 25 to 50 percent more when the duplex pumps are in only ordinarily fair working shape. This statement may possibly surprise many who have based their opinions on the too commonly accepted fact that all direct-acting pumps are equally wasteful steam users.

In line with the above facts general conditions should determine the type of pump most suitable for a given service. If the pump is likely to be roughly handled, exposed to bad weather, and subject to neglect—or if in the pump installation the steam after being used in the pump can all be profitably utilized for plant process purposes, etc., then the duplex pump will well fit the case.

If on the other hand, conditions are such that maximum economy in operation is sought, together with high efficiency generally, then the simplex pump is the logical unit. It is nevertheless true that many pump installations are based not on facts as above presented, but on the engineers' preference for either one or the other type, due to long familiarity with duplex and simplex pumps as the case may be.

In conclusion it should be noted that the steam pump is not an out-of-date machine but rather one that has a great many uses for which there is no substitute. For those who will spend the time to study the conditions of service, particularly with respect to intake conditions and apply and operate steam pumps carefully, there are rich rewards in plant economies. ——— ☆ ☆ ☆

FUEL OIL FIRING VALVES



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Operating Features of the Katy Gas Cycling Plant*

By

FRANK G. NOBLE

Natural Gas and Gasoline Department, Humble Oil and Refining Company

Introduction

THE Katy gas field, Texas, is situated principally in the southeastern corner of Waller County with its outer limits extending into the southwestern corner of Harris County, and the northeastern corner of Fort Bend County.

In 1939, negotiations were begun with the parties having interests in the Katy gas field for the unitization of their properties with the view of installing a cycling plant to process the produced gas for the recovery of desired liquid hydrocarbons and reinjection of the unsold residue gas into the producing sands for the purpose of gas conservation. Agreements of interested parties regarding basic contracts for the project operation were completed by May, 1941.

After completion of these basic contracts, immediate plans were drawn for the installation of a gas cycling plant, the purpose of which, in addition to the above operations, is to recover the essential products of butanes, gasoline, and other hydrocarbon fractions to be utilized in the manufacture of aviation gasoline, rubber, toluene, and other products.

It might be of particular interest to discuss briefly some of the features of the plant design and operations regarding methods employed in handling the high-pressure gas, extracting the desired products, processing of gas for gas sales, the unusual arrangement and operation of the steam system, as well as other design features.

Plant Design

Recent trends in the design of most gas cycling plants have been toward the installation of plants with large gas processing capacity, usually 100 to 200 million cu. ft. of gas per day. Considerable study was given to the proper size plant to produce the Katy gas field, and it was concluded that a plant of the oil absorption type with a processing capacity of 275,000,000 cu. ft. of gas per day would permit economical processing of the gas over a period of 30 to 40 years.

The plant is designed to process 275,000,000 cu. ft. per day of gas from the producing wells, recovering 80 percent of the potential butanes and practically all pentane and heavier hydrocarbons. Approximately 235,000,000 cu. ft. per day of wet gas will enter the four high-pressure absorbers operating at 1800 lb. per sq. in. The absorber residue gas, at a volume of about 210,000,000 cu. ft. per day, is to be returned by the gas engine-driven compressor units to the injection wells. The remaining plant capacity is utilized in the processing of gas for delivery to two sales gas transmission systems. The rated capacity for delivery to gas sales is approximately 52,000,000 cu. ft. per day; however, the absorption equipment is sized to accommodate a reasonable overload in order to handle peak gas sales demands.

The plant at rated capacity is expected to recover approximately 7500 bbl. per day of total products. Stabilization and storage facilities are provided for the separation of (1) butanes, (2) 250°F. endpoint gasoline, and (3) heavy distillate, as separate products. The expected production is 1661 bbl. per day of butanes, 2689 bbl. per day of gasoline, and 3164 bbl. per day of naphtha and distillate.

Field System

The gathering system is designed to take the unit's gas from 15 producing wells, three of which are dual completions. The lines are sized for a maximum daily production of 20,000,000 cu. ft. each from the edge wells, 25,000,000 cu. ft. each from the other single-sand completions, and 40,000,000 cu. ft. from dual completions. To allow for future production from the weaker and lower pressure wells in the upper sands, the lines are designed for a pressure drop of 200 lb., assuming 2200 lb. per sq. in. at the plant and 2400 lb. per sq. in. at the well meter settings. The gathering system is designed for a working pressure of 2700 lb. per sq. in. at 130°F.

Each producing well is equipped with a meter setting for metering the gas produced from each sand. For the lower sand wells there is a single wing casing and tubing connection with 2-in. adjustable chokes for controlling the flow. For the upper sand single-completion wells the casing is connected by a double 4-in. wing, and the tubing by a single wing connection equal in size to the tubing. Each wing has an adjustable choke for controlling the production rate. For dual completion wells the wellhead connections are the same as for the upper sand wells.

The injection system for returning gas to the injection wells is planned so that reasonable distribution control may be maintained. Control of the gas cycling "pattern" will necessitate variations in gas injection rates to the various wells during the period of operations. The injection field lines are designed so that approximately 50,000,000 cu. ft. could be delivered to each injection well with a maximum pressure drop of 100 lb. between the compressors and the injection wellheads. Of this pressure drop, about 25 lb. is due to line losses at the plant, expansion bends, meter setting, and wellhead connections.

A comparison was made of the merits of individual lines between the plant and the injection wells as against a large line from the plant to each end of the field with laterals to each injection well. It was found in this particular case that, for a given pressure drop, the individual lines had about 25 percent more capacity, required approximately 250 tons less steel, and resulted in a lower installation cost.

The injection field lines are 7⅝-in. O.D. (0.625 in. wall thickness) pipe. The meter setting and pipe within 125 ft. of the injection well are 6⅝-in. O.D. (0.718 in. wall thickness) pipe. All piping is designed and constructed in accordance with the A.S.A. Code for High Pressure Piping, using Grade B seamless pipe. Each injection well has two 4-in. casing and one 2½-in. tubing connection with a check valve installed on each wellhead connection. The field lines are securely anchored at each end and between each expansion bend provided in the line. Expansion bends are also installed at the wellhead to provide for expansion in the well casing. The injection system is designed for a working pressure of 3500 lb. per sq. in. at 175°F.

Plant Gas System

The attached plant "Flow Diagram," Fig. 1, illustrates the essential features of the plant process design and is to be referred to in illustrating the various systems involved.

The producing wells, at an average flow rate of 25,000,000 cu. ft. per day each, have a pressure at the wellhead of approximately 2450 lb. per sq. in. and a flowing temperature of 165°F. The wet gas arrives at the plant at a pressure of 2200 lb. per sq. in. and a temperature of about 135°F. The gas, to be processed in the high-pressure absorbers and handled through the compressor unit for reinjection to the pro-

*Presented before Southwestern District American Petroleum Institute Division of Production, Houston, Texas, April 29 and 30, 1943.

ducting formation, is first cooled in the high-pressure cooling coils situated in the cooling tower. Such cooling reduces the gas temperature from 135°F. to 90°F. at inlet plant pressure. After cooling, the gas is delivered to the 1800-lb. system through two headers and pressure-reducing regulators that control the absorber and compressor suction pressure at 1800 lb. per sq. in. Before introducing the gas into the four 1800-lb. absorbers, it is passed through two separators operating in parallel to remove the liquid formed by previous cooling and pressure reduction. The discussion of this liquid flow will follow under the "Condensate Flash and Process System."

Gas from the separators operating at 1800 lb. per sq. in. is next delivered and equally distributed to four absorbers operating in parallel. Sufficient absorption oil contacts the gas for the extraction, at this point, of 84 percent of the butanes. The residue gas is then passed through two scrubbers in parallel operation where any entrainment or large quantity of liquid that might be carried overhead from the absorbers, due to mechanical "up-set," will be automatically collected and drained. The gas then goes into the compressors for delivery to the injection wells. All gas volumes referred to in this discussion are at a pressure base of 14.7 lb. per sq. in. absolute and 60°F. temperature.

The compressor unit has seven 800-hp. compressors, each machine consisting of two double-acting horizontal compressor cylinders directly connected to an 8-cylinder power engine operating at 330 r.p.m. The compressors are installed to deliver 210,000,000 cu. ft. per day of high-pressure absorber residue gas to the injection system and wells at a suction pressure of 1800 lb. per sq. in. and a discharge pressure of 3000 lb. per sq. in. A closed jacket cooling water system is provided for the unit, the make-up water being condensed steam from the power plant system. The jacket water coolers are of the closed shell-and-tube type and are arranged with a bypass and necessary control equipment to maintain the desired jacket water temperature. A 100-hp. electric-motor-driven centrifugal pump circulates the required quantity of jacket cooling water.

Sales Gas System

Facilities for supplying the high-pressure residue gas for sale to the two gas transmission systems in the field center primarily around the operation of two 800-lb. sales gas absorbers and the 600-lb. high-pressure reabsorber. A stream of the wet gas from the field producing wells is withdrawn upstream from the high-pressure gas coolers and reduced to 800-lb. per sq. in. by means of an instrument-operated control valve. Due to pressure drop, the temperature of the gas will be lowered from 135°F. to approximately 80°F. A heater is installed in the line to prevent hydrate formation at low temperatures. The gas, along with the liquid formed by pressure reduction, is next delivered to the sales gas separator where the liquid is removed and the gas passed to the two sales gas absorbers operating in parallel. Sufficient absorption oil contacts the inlet gas to extract approximately 79 percent of the butanes. The residue gas, after leaving the absorbers, goes to a 600-lb. operating pressure stop tank where it is commingled with the residue gas from the reabsorber and with the recompressor discharge vapors. The total gas from this stop-tank then passes through control equipment and into the sales gas systems. The control scheme of the system is such that either constant gas volume or constant pressure may be maintained on one of the gas systems, whereas gas delivery to the other system is designed for constant pressure only. A primary pressure-reducing regulator on the high-pressure inlet wet gas floats on the line so as to maintain 800 lb. per sq. in. on the sales gas absorbers regardless of the variations in sales gas deliveries.

Reabsorption System

One of the major problems encountered is the design of a process employing a pressure in the primary absorbers of 1800 lb. per sq. in. is the proper removal of the tremendous quantities (approximately 16,000 M. cu. ft. per day) of methane and ethane dissolved in the rich oil from the absorbers. The most practical method of eliminating these undesirables, and yet retaining butanes, is by stage reduction of pressures and reabsorption of the desirable hydrocarbons. Careful consideration was given in the design to selection of the optimum pressures for these flashes and reabsorptions. As a result, the rich oil from the 1800-lb. absorbers combines with that from the sales gas absorbers and is flashed successively at 600, 200, and 35 lb. per sq. in. The flashed gases are contacted at respective pressures in the reabsorber for the desired butane retention. The residue gas from the high-pressure reabsorber is delivered to the sales gas system. The residue gas from the intermediate pressure reabsorber is used for plant fuel, any excess being recompressed, cooled, and delivered to the sales gas system, the residue gas from the low-pressure reabsorber supplies fuel for the boilers and direct-fired heaters. It is not necessary under the above system of rich oil flashes and reabsorptions to design for a high percent butane extraction in any of the reabsorbers. The favorable result is in that the rich oil feed to the still system contains a minimum of dissolved methane and ethane hydrocarbons.

Condensate System

A separate system is provided for processing the liquid formed by retrograde condensation and separated from the gas in the 1800-lb. and 800-lb. sales gas separators. It may be of interest to point out several of the factors that influence the selection of this design.

(1) To eliminate possible future difficulties with salt water or other contamination of the absorption oil system,

(2) To relieve the steam stripping loads on absorption oil stills,

(3) To permit partial operation of the plant when units of the absorption plant are shut down, and

(4) To give added flexibility for varying the endpoint of the gasoline product.

The liquid separated in the 1800-lb. inlet gas separators is flashed into the sales gas separator, operating at 800 lb. per sq. in. This permits reabsorption of the flashed gases at optimum pressure and reduces the quantity of field wet gas required to supply the sales gas demands. The 800-lb. separator liquid is further flashed in stages to 600, 200, and 35 lb. per sq. in., the flashed gases going to the previously mentioned reabsorbers operating at these respective pressures. In this manner, all flashed vapors are properly processed in the reabsorption system for the retention of the desirable butanes. The liquid from the low-pressure condensate flash tank is delivered by pump through heat exchangers, a preheater, and into the condensate still operating at 45 lb. per sq. in. Sufficient stripping steam is introduced into the base of the still to effect the removal of all the 250°F. endpoint and lighter hydrocarbon fractions, the overhead vapors passing through a condenser where approximately 90 percent condensation is obtained. External reflux is returned by the reflux pump to the top of the still for the desired endpoint control of the overhead product, while the net overhead product is introduced as liquid into the vapor stream from No. 1 still, just upstream of the final product condensers. The product from the base of the condensate still is heat exchanged against the feed material and then delivered to storage as gasoline free distillate.

Distillation System

The primary purposes of the distillation system are to process the rich oil from the absorption unit, remove the

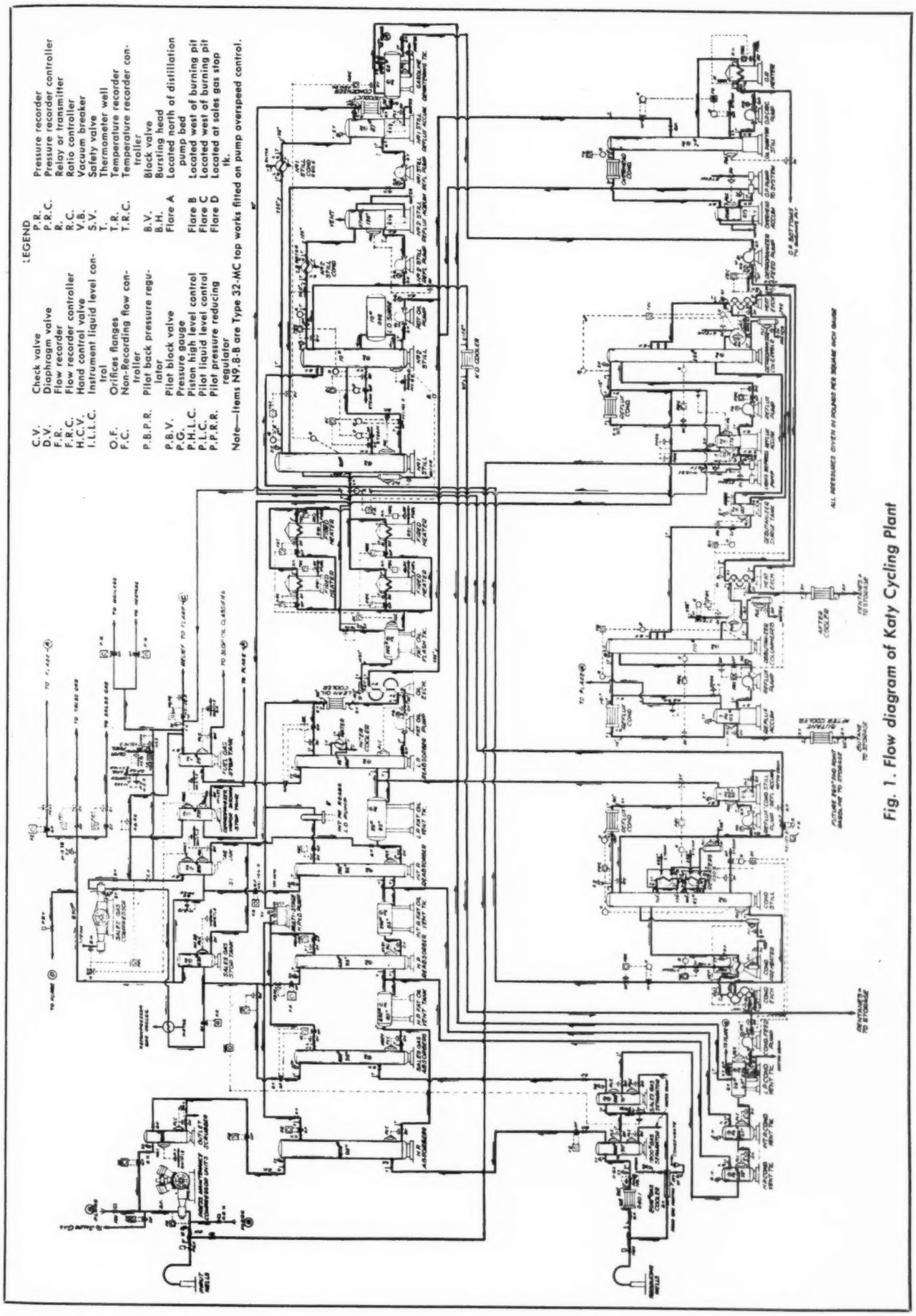
LEGEND
C.V. Check valve
D.V. Diaphragm valve
F.R. Flow recorder
F.R.C. Flow recorder controller
H.C.V. Hand control valve
I.L.L.C. Instrument liquid level control
O.F. Orifices flanges
F.C. Non-Recording flow controller
P.B.P.R. Pilot back pressure regulator
P.B.V. Pilot block valve
P.G. Pressure gauge
P.H.L.C. Piston high level control
P.L.C. Pilot liquid level control
P.P.R.R. Pilot pressure reducing regulator
P.R. Pressure recorder
P.R.C. Pressure recorder controller
R. Relay or transmitter
R.C. Ratio controller
V.B. Vacuum breaker
S.V. Safety valve
T. Thermometer well
T.R. Temperature recorder
T.R.C. Temperature recorder controller
B.V. Block valve
B.H. Bursting head
Flare A Located north of distillation pump bed
Flare B Located west of burning pit
Flare C Located west of burning pit
Flare D Located at sales gas stop tk.
Note—Items N9.8-B are Type 32-MC top works fitted on pump overspeed control.

Fig. 1. Flow diagram of Katy Cycling Plant

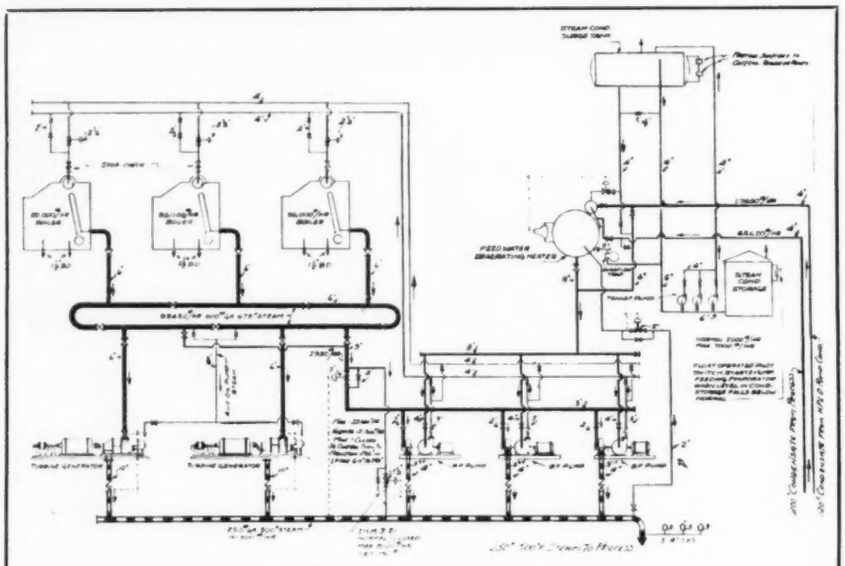

Fig. 2. Flow diagram of power plant

desired gasoline fractions, and provide a well-stripped heavy absorption oil for recirculation to the absorption system. To accomplish these, it is necessary to operate a two-still system. The No. 1 still, operating at 90 lb. per sq. in., is designed to remove the 250°F. endpoint gasoline product from the rich oil. This is accomplished by pumping the rich oil from the absorption system through heat exchangers and direct fired heaters to bring the temperature level to 530°F. Sufficient stripping steam effects the removal of the desired overhead fractions whereas a hot reflux controls the gasoline final boiling point. The liquid condensed from the overhead of this still provides the raw charge to the stabilizers.

Oil leaving the base of the No. 1 still contains hydrocarbons boiling between 250°F. and 500°F. The No. 2 still, operating at 5 lb. per sq. in., receives this oil feed for further processing at approximately 500°F. Sufficient stripping steam removes the heavy hydrocarbons and gives control on the initial boiling point of the absorption oil from the bottom of the still. The stripped absorption oil is next pumped through the heat exchangers and final oil coolers and to the various absorbers. The overhead product is condensed and delivered to storage with the bottoms from the condensate still.

The absorption oil for the sales gas absorbers and the high-pressure reabsorbers is withdrawn as a side stream from the main high-pressure lean oil pump. The pump for delivering the oil to these absorbers is a 1900-hp. steam-turbine-driven centrifugal unit. It is designed to handle a normal load of 1340 gal. per min., 250 gal. per min. being withdrawn at 800 lb., while 1090 gal. per min. is pumped to the four high-pressure absorbers operating at 1800 lb. per sq. in. The total absorption oil circulation for the plant amounts to 1673 gal. per min. of 36-degree A.P.I.-500°F. initial boiling point oil.

Stabilization Unit

The stabilization unit is designed to produce two finished products. They are (a) a mixture of butanes, with or without propane, and (b) a butane-free specification endpoint gasoline. These products, in addition to the heavier fractions from the distillation system, constitute the plant's total production.

The stabilizer scheme followed in the plant design is similar to the arrangement of most stabilizer installations. The depropanizer unit, however, has one particular feature that is seldom found in other plants of this nature. The raw gasoline feed material, containing a small quantity of methane and ethane hydrocarbons, is pumped into the depropanizer operating at 285 lb. per sq. in. Practically total condensation is obtained on the overhead material of propane and lighter hydrocarbons upon cooling this stream for reflux.

A turbine-driven triplex repressuring pump with 285-lb. suction pressure and 3400-lb. discharge pressure will handle all excess reflux, thus permitting the return of this material as a liquid into the discharge header of the main gas compressors and hence to the injection wells. This method of operation affords a saving in investment as well as the elimination of a recompressor, thereby reducing the operating expenses.

The liquid from the depropanizer reboiler, consisting of the butanes and heavy hydrocarbons, is next fractionated in the debutanizer column. Here the butanes are removed as an overhead specification product, while the final gasoline is withdrawn as a bottom product. The butanes are condensed and transferred to two 5000-bbl. spherical tanks for storage; the gasoline fraction is cooled and delivered to three 5000-bbl. spherical storage tanks.

Humble Pipe Line Station

The Humble Pipe Line Company has a pump station on the plant site to handle deliveries of the plant products to the Humble Oil and Refining Company's Baytown Refinery. The butane product is pumped to the Satsuma-East Texas gasoline line through 17 miles of 4-in. pipe. The gasoline and heavier products are pumped through nine miles of 4-in. pipe line to the Raccoon Bend pumping station.

Steam and Power System

Steam. The steam and electric system for the Katy Gas Cycling Plant is quite unusual as compared with that found in most plants of this nature. During the preliminary discussions of the plant design, it was decided to use steam and electrically-driven centrifugal pumps where practicable. The plant process required approximately 95,000 lb. of steam per hour at 250, 105, and 15 lb. per sq. in. pressure, and an electric power and lighting load of 1740 kw.

Comparisons were made of the various combinations of steam and electric drives for the different services and combinations of condensing and noncondensing steam plants operating at 250 and 600 lb. per sq. in. steam pressure. These comparisons included installation and operating costs and trial heat balances.

After analyzing the various power schemes, the most attractive was the generation of steam at a pressure of 600 lb. per sq. in., generating the required electrical load by back-pressure steam-turbine-driven generators, and staging the steam pressures down through the plant so that the total steam required for the generator drives balanced the requirements for process heating, stripping, and pump drives.

A brief discussion of the steam system will illustrate the principal features of interest. The "Flow Diagram," Fig. 2, shows the arrangement in the power plant, and Fig. 3 details the methods of utilizing the steam in the distillation system.

To meet the processing requirements of steam, three 700-lb. working pressure boilers are installed. Each boiler is designed to produce 50,000 lb. per hour steam at 600-lb. pressure and 675°F.

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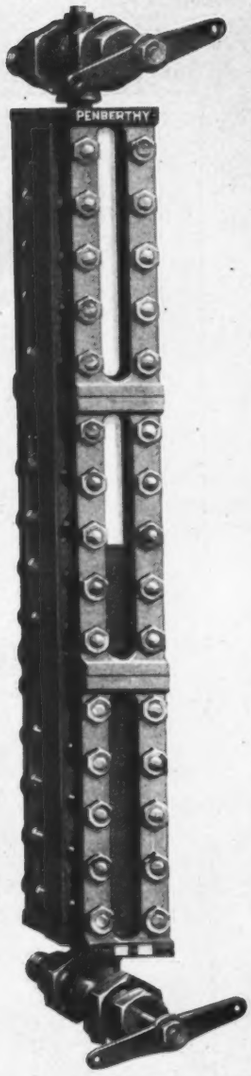

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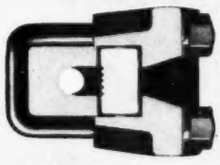

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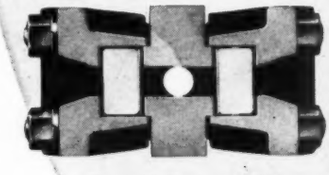

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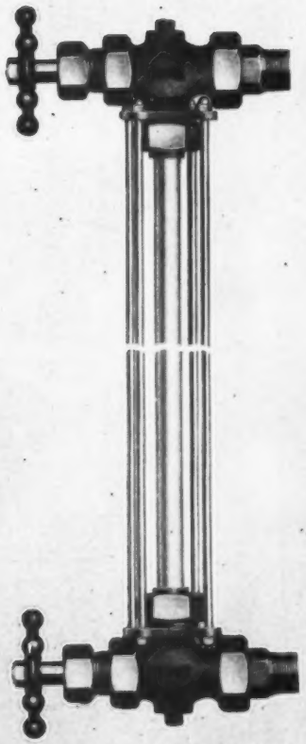

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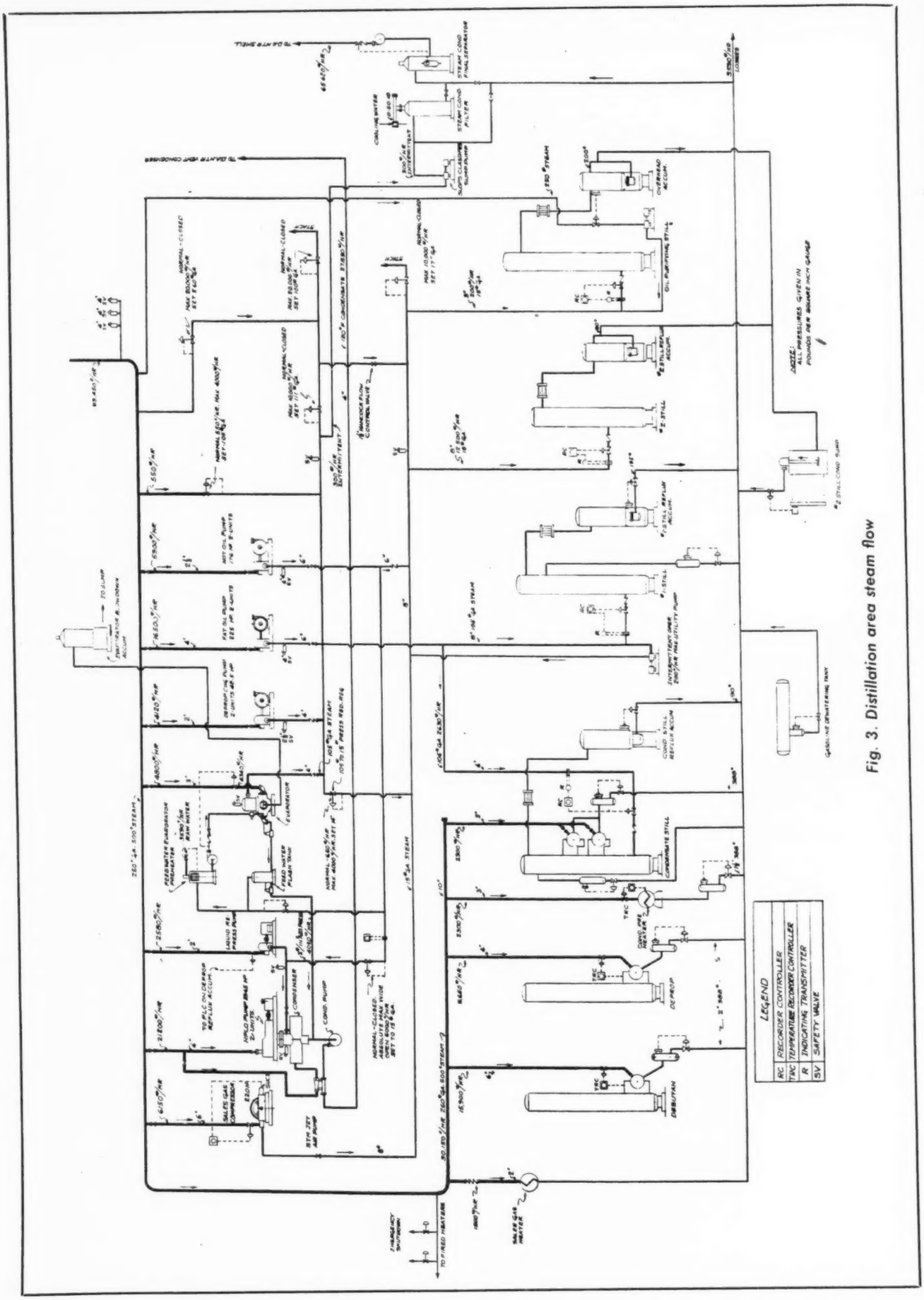

Fig. 3. Distillation area steam flow

temperature. The boilers are of the integral furnace type, completely water walled, and equipped with forced- and induced-draft fans with stub stacks.

For the calculated electrical load of 1740 kw., there are installed two 2000-kw., 480-volt, 3-phase, 60-cycle, 3600-r.p.m. turbo-generators. The turbines operate at 600-lb. inlet steam pressure and throttle to 250-lb. back pressure. Normally, two boilers and one turbo-generator will be operated.

Steam from the 600-lb. header is used to drive the generator and boiler feed pump turbines, the exhaust pressure from these turbines being maintained at 250 lb. per sq. in. The exhaust steam at 250-lb. per sq .in. is next utilized in the distillation unit process for heating, stripping, and driving certain pumps. The steam as utilized in these services is all condensed and returned to the deaerating heater for feed to the boilers. An elevated surge tank maintains constant make-up water to the heater and any excess water overflows to the storage tank. The pumps at the storage tank are operated automatically to maintain proper water level in the surge tank, and a float-operated switch controls the operation of the make-up evaporator to maintain constant water level in the tank.

There are three dual-drive centrifugal feedwater pumps, operating at 3550 r.p.m. each, driven through a flexible coupling by a 150-hp. motor at one end and by a steam turbine at the other.

An automatic regulating valve in the steam line to the three turbines divides the power input to the pumps between the turbines and motors for the purpose of controlling the steam pressure in the 250-lb. exhaust header.

Complete automatic combustion control equipment is installed on each boiler for maintaining pressure, forced draft, furnace draft, and induced draft.

The distribution and utilization of the steam from the boiler house at a pressure of 250 lb. per sq. in. is one of the most interesting systems in the plant. Approximately 56,450 lb. per hour of steam is required for driving the various pumps in the distillation system, whereas 36,450 lb. per hour are utilized in heating in the stabilizer reboilers, the condensate still preheater and reheaters. A steam demand of approximately 25,000 lb. per hour at a pressure of 105 lb. per sq. in. is required for stripping in the No. 1 still and condensate still. The turbines driving the fat oil pumps and the depropanizer charge pump are of the back-pressure type, exhausting into a 105-lb. steam header. The steam from the make-up evaporator goes into this header. The 105 lb. steam is next used in stripping as illustrated. The quantity of stripping steam required at 15 lb. per sq. in. is 12,700 lb. per hour. To provide this steam, the turbines driving the hot lean-oil pump and recompressor exhaust into a steam header operating at 15 lb. per sq. in. The pressure in the 15-lb. steam header is controlled by means of a pressure-reducing regulator from the 105 lb. system. Sufficient regulating and relief valve equipment is installed to prevent excessive pressure in any of the steam headers during either partial or full-load operation.

The centrifugal oil pump, delivering absorption oil to the high-pressure absorbers, is driven by a 2000-hp. steam turbine operating at 3600 r.p.m. The inlet steam is at a pressure of 250 lb. per sq. in., and the turbine exhaust steam is piped into a 2800 sq. ft. surface condenser operating under four inches mercury back-pressure. The exhaust steam from the turbine driving the liquid repressuring pump along with any excess steam from the 15-lb. steam header is also introduced into this surface condenser. The condensate from the hot well of the condenser is returned by pump to the deaerating heater in the power plant.

The condensed steam from the various units of distillation equipment is returned to a steam condensate filter and separator system where any trace of oil or contamination will be removed and the condensate returned by centrifugal pump to the deaerating heater situated in the boiler plant.

This method of operation assures practically total return of condensed steam for feed to the boilers. The expected make-up requirement is less than 5000 lb. per hour.

Electrical

The main switchboard in the power plant is of the dead-front, metal-enclosed type with draw-out circuit breakers and interconnecting bus structures for the control of the underground system rated at 440-volt, 3-phase, 3-wire, 60-cycle current. Main generator and feeder panel breakers are electrically operated with the distribution panel breakers being manually operated with inverse time delay trip and several are equipped with shunt electric trip.

Two sets of underground cables are run in separate fiber ducts buried in concrete to separate bus ducts in the switch houses situated near the cooling tower, distillation unit pump building, and the compressor building, each set being protected by a circuit breaker in the power house. In order to insure continuous operation of these essential units, half of the motor load at each center will be on the breaker on distribution board "A" and half of it on board "B." Motor load in the power plant is divided in the same manner. The system is balanced so that the entire load is almost exactly equal on the two feeder breakers.

Each motor at load centers has an explosion-proof push button near it. Standard line starters and circuit breakers are situated in the switch houses.

Plant Safety Features

The necessity for providing safety devices in an average gasoline plant is obvious. In a large high-pressure cycling type plant, it is of utmost importance to give particular attention to safety features. The safety arrangements, although sometimes very simple, act as guards to warn of trouble, and also to protect the equipment against damage. There are many safety features of interest in the Katy plant, a few of which will be briefly discussed.

1. Emergency high-pressure gas control system. In order to protect the plant in case of failure in the high-pressure gas system, piston-operated plug valves are installed on both the producing and injection lines at the plant boundary. These valves are oper-

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ated from a series of manually operated control stations strategically placed in the plant operating area. Such operation will shut off the incoming and outgoing gas, as well as shutting down the compressor unit. At the same time, another piston-operated valve will open to permit the blowing down of the high-pressure gas within the plant to a flare stack situated on the south boundary of the plant yard.

2. **Protection of direct-fired heaters.** The direct-fired heaters have both a hand-operated steam snuffing system and an emergency snuffing system, which may be operated in case of tube failure or fire. As a protection against the loss of oil flow through the heaters, which may happen in the event the rich oil pump fails, the fuel gas will automatically be shut off, thus reducing the hazard of coking up the heater. A third feature is that a failure of fuel gas supply will automatically close the fuel regulator, which must be manually reset, thus eliminating a fire hazard.

3. **General alarm system.** In order to warn the plant operator of trouble in the system, an arrangement of alarm whistles is installed on the various vessels requiring special attention against certain adverse operating conditions. If the problem is beyond the operator's control, however, another set of safety controls will automatically shut down the major mechanical equipment, thus insuring protection against damage.

Cooling Water System

In a cycling plant of usual design, having the capacity of the Katy plant, the quantity of cooling water circulation would be approximately 20,000 gal. per min. By a careful balance of heat requirements and equipment installation, the Katy plant requires only 14,000 gal. per min. This reduction is a result of balancing the cooling loads for the closed shell-and-tube type condensing and cooling equipment against the cooling required for the atmospheric cooling sections situated in the base of the cooling tower. Approximately 14,000 gal. per min. is required over the coils in the cooling tower. The water in passing over these coils increases in temperature from 85°F. to 95°F. This 95°F. water is then pumped in parallel flow through the shell and tube equipment of (1) engine jacket water coolers, (2) exhaust steam condenser, (3) No. 1 still primary reflux condensers, and (4) No. 2 still primary reflux condensers. The water, after passing through these units, is delivered over the top of the cooling tower for distribution and reduction in temperature from 115°F. to 85°F., thus completing the cycle of water flow.

Raw water for the plant make-up is supplied from water wells in the plant yard. A 500-gal. per min. pump delivers water from the water wells to a 3000-bbl. settling tank. This make-up water, in its route to the cooling tower, is utilized for cooling in the low-pressure reabsorber intercooler and various other minor cooling duties required in the power and distillation unit equipment. The raw water supply is also connected to the plant camp and to all fire systems.

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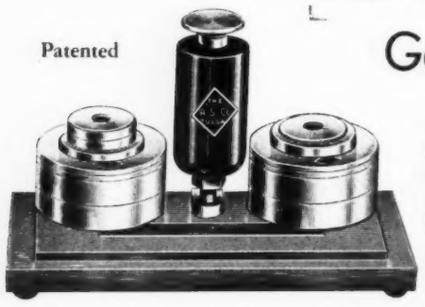

A practical and exact means of checking: Rock Pressure at Wells, Static Pressure on orifice meters and Gas Pressures on pipe line leakage tests.

This device will measure any gas pressure to a higher degree of accuracy. It *does not* have to be handled gently. It never has to be checked or calibrated. Weights are brass, stacked on posts on same base as the tester. Available in Standard and High Pressure models. Delivered complete with weights and hardwood carrying case.

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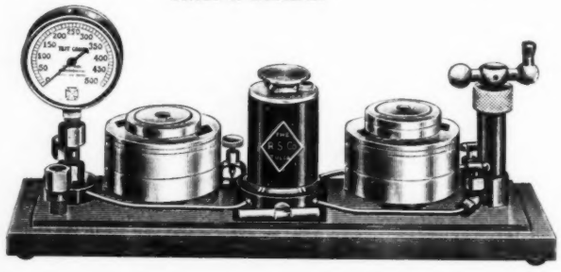
The accuracy of these instruments is checked by the use of a master tester calibrated by the Bureau of Standards.



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Measurement and Control in the Natural Gasoline Plant*

By C. G. CORTELYOU

Measurement Engineer, General Petroleum Corp. of California

THERE are many basic factors upon which the design and operation of the natural gasoline plant must depend. Some of these are modified by existing economic and local conditions and much of the theory behind the design must be practically tested and confirmed. In the measurement and control of the various fluids with which the plants are operated, these basic factors are continuously being tried and developed. In presenting this paper, therefore, it is the hope of the Southern California Meter Association and the author, that some practical helpful information may be given for the construction of new natural gasoline plants as well as for the better operation of those now in service.

As natural gasoline plants are designed and operated for the production of various petroleum fractions at a profit to the owner, it is self-evident that the installation of any machinery, meters, regulators, or control equipment not definitely necessary to the efficient and economical operation of the plant, constitutes a poor investment. Moreover, simplicity of design provides for better and more easily maintained plant control. It is a design axiom therefore, that to hold the capital and maintenance expense to a minimum, no meter or regulator should be provided except when they serve a necessary purpose. The following discussion will perhaps serve to indicate the necessary locations of meters and control equipment within the gasoline plant and the reasons for each installation.

General Factors

To begin with, there are different standards of measurement and regulation that should be set up for each phase of the plant operation. Orifice meters that are involved in the measurement of lessors gas for royalty settlement, or for determination of plant balances, should conform to existing code standards as shown in Figs. Ia, Ib, Ic, and Id. As suggested by Frank West of the Texas Company in a paper before the S.C.M.A. in 1939, these could be termed "code" meters. In contrast to this, the "non-code" meters might be used for plant control and measurements of a less vital nature, where an accuracy of within 1 percent or 2 percent was sufficient. On "non-code" orifice meters for instance, the length of the meter tubes might be shortened and standard pipe and flanges used without particular regard for tolerances.

Similarly, there are certain standards of temperature and pressure that must be maintained within the plant if maximum yield and uniformity of product are to be maintained. The quality of certain plant products depends upon the accurate control within tenths of a degree F. of the process temperature, whereas other phases of the process may be allowed greater variance. These standards and the controls necessary to maintain them will be indicated as each section of the plant is discussed.

There are several general recommendations that will apply to all meters and control equipment throughout the plant. The first of these is in regard to orifice meters and should be particularly stressed, both from a standpoint of accurate measurement and for proper maintenance of equipment. It is the regular periodic inspection of orifice meter plates and checking of meter gauges. Although no time limit can be set for all types of meter service, it is felt that all meters and plates should be checked at least every 90 days and most locations oftener. By making these regular inspections, any deviation of the plates from standard dimensions due to abrasive or corrosion action can be detected. It also enables the meterman to keep the gauge in proper working order, so the major repairs are cut to the minimum.

If the orifice meter plates are to be regularly inspected it will be necessary for provisions to be made for the removal of the plate without shutting the line down, as this is seldom practicable in the natural gasoline plant. This means the installation of a bypass around the meter run or the use of an orifice fitting that will permit removal of the plate while the line is in service. It has been the general experience of the industry that the price of either of these two alternatives is comparable, so from a standpoint of space conservation it is generally recommended that orifice fittings be used.

Fig. Ie illustrates the specifications for orifice meter plates as given in C.N.G.A. Bulletin T.S.-353. It will be noted that bevel edge orifices are required in many cases in order to conform to these standards for the measurement of natural gas. In general, the beveling is not found necessary for the measurement of the various plant liquids or steam.

An occasional source of error in an otherwise perfect meter set-up, is the improper installation of gaskets between the tube flanges and the orifice fitting. The joint when properly gasketed should present a smooth inner surface, as any projection of the gasket within the inner diameter of the bore invalidates all the careful machining and alignment that have been done to maintain fixed orifice conditions.

It will be desirable at times to obtain samples of the fluids flowing through the meter runs so that specific gravity determination or other tests may be made upon them. For this purpose a center line sampling tap should be installed at the downstream end of the meter run to enable a representative sample of the fluid to be drawn off. Just downstream of this connection a thermometer well of the correct size should be installed to obtain information for the temperature correction factor in the meter coefficient. When a recording thermometer is to be installed, it is recommended that a second well be provided for checking the instrument against a glass bulb thermometer. Under certain conditions of flow where the temperature of the flowing fluid is markedly different from the ambient temperature, it may be found advisable to install an insulated thermometer well in the line. This will prevent the rapid dissipation of heat to or from the bulb of the thermometer and will help to eliminate error from this source. In any case, the thermometer well should be installed either vertically or at an angle above the horizontal so that liquid may be introduced into the space between the well and the thermometer bulb to aid the transfer of heat from one to the other. It will be found that heavy oil is satisfactory for this use in most cases.

Automatic Control

As has been indicated, the role of the automatic controller and motor valve is one of prime importance to the natural gasoline plant. In fact, it might be said that the rapid strides made by the industry in increasing the quality of their various hydrocarbon products has been largely due to the development and widespread use of temperature and pressure controllers. As we all know, the modern controller has come a long way since the days of simple "on-off" control.

A general criterion for a good controller and its associated control valve, is that the valve lift should be proportional to pen movement throughout the range of valve and instrument travel

*Presented before California Natural Gasoline Association, July 2, 1942.

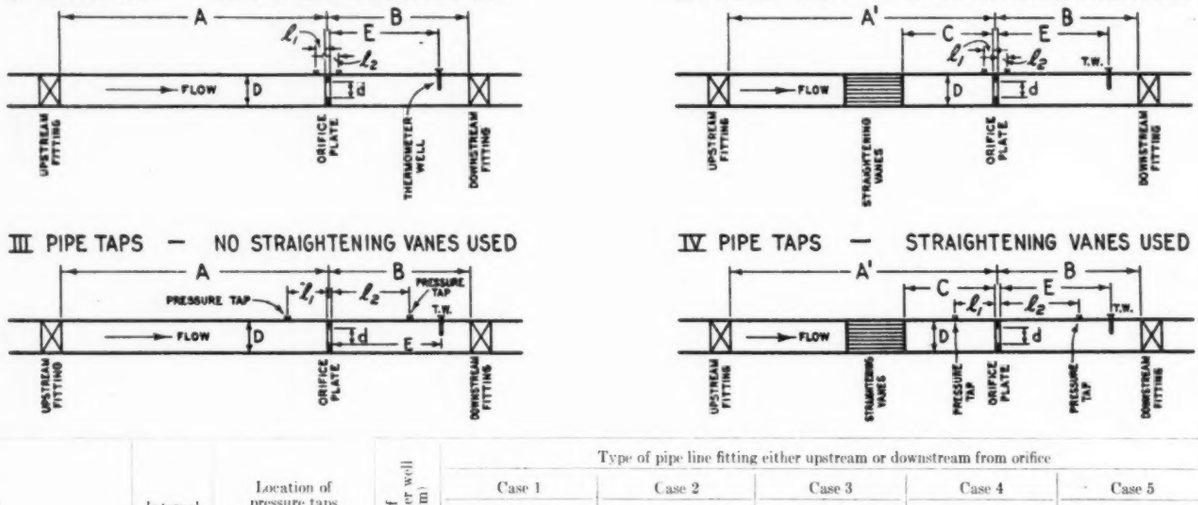
and that equal percentage increments of valve lift should produce equal increments of flow. With the selection of a properly designed valve for the desired capacity and pressure drop conditions, the "floating or continuous" type controller may be set to maintain extremely accurate temperatures and pressures.

In designing the control installation, thought should be given to the possibility of the control air or gas being shut off. This is especially true during

Fig. 1a

Minimum straight lengths of standard sized meter tubes for various types of upstream and downstream pipeline fittings

Reference: 1935 U. S. Bureau of Standards and American Gas Association Specifications



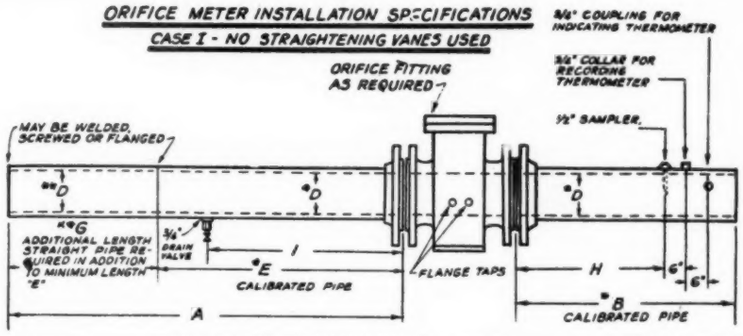
	Internal pipe dia. "D" in inches	Location of pressure taps		Location of thermometer well E (minimum)	Type of pipe line fitting either upstream or downstream from orifice														
					Case 1			Case 2			Case 3			Case 4			Case 5		
					Swedge either increasing or decreasing			One bend			Two bends in same plane			Two bends not in same plane			Regulator control valve, etc.		
		l_1	l_2		A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
				3D+1"	13.5 D	4.5 D		16.5 D	4.5 D		21.7 D	4.5 D		34.2 D	4.5 D		44.5 D	4.7 D	
I	2.067	1.00"	1.00"	0′ 8"	2′ 4"	0′ 10"		2′ 11"	0′ 10"		3′ 9"	0′ 10"		5′ 11"	0′ 10"		7′ 8"	0′ 10"	
Flange taps	3.068	1.00"	1.00"	0′ 11"	3′ 6"	1′ 2"		4′ 3"	1′ 2"		5′ 7"	1′ 2"		8′ 9"	1′ 2"		11′ 5"	1′ 3"	
no straightening	4.026	1.00"	1.00"	1′ 2"	4′ 7"	1′ 7"		5′ 7"	1′ 7"		7′ 4"	1′ 7"		11′ 6"	1′ 7"		15′ 0"	1′ 7"	
vanes used	6.065	1.00"	1.00"	1′ 8"	6′ 10"	2′ 4"		8′ 5"	2′ 4"		11′ 0"	2′ 4"		17′ 4"	2′ 4"		22′ 6"	2′ 5"	
	8.071	1.00"	1.00"	2′ 2"	9′ 1"	3′ 1"		11′ 2"	3′ 1"		14′ 8"	3′ 1"		23′ 1"	3′ 1"		30′ 0"	3′ 2"	
Maximum ratio	10.19	1.00"	1.00"	2′ 8"	11′ 6"	3′ 10"		14′ 1"	3′ 10"		18′ 6"	3′ 10"		29′ 1"	3′ 10"		37′ 10"	4′ 0"	
(d/D)=0.75	12.09	1.00"	1.00"	3′ 2"	13′ 8"	4′ 7"		16′ 8"	4′ 7"		21′ 11"	4′ 7"		34′ 6"	4′ 7"		44′ 11"	4′ 9"	
	15.25	1.00"	1.00"	3′ 11"	17′ 2"	5′ 9"		21′ 0"	5′ 9"		27′ 7"	5′ 9"		43′ 6"	5′ 9"		56′ 7"	6′ 0"	
	19.182	1.00"	1.00"	4′ 11"	21′ 7"	7′ 3"		28′ 5"	7′ 3"		34′ 9"	7′ 3"		54′ 9"	7′ 3"		71′ 2"	7′ 7"	
II	D	l_1	l_2	E	A′	B	C	A′	B	C	A′	B	C	A′	B	C	A′	B	C
				3D+1"	15.5 D	4.5 D	7.2 D	16.5 D	4.5 D	7.2 D	13.7 D	4.5 D	7.2 D	14.4 D	4.5 D	7.2 D	17.0 D	4.7 D	7.2 D
Flange taps	2.067	1.00"	1.00"	0" 8"	2′ 9"	0′ 10"	1′ 3"	2′ 11"	0′ 10"	1′ 3"	2′ 5"	0′ 10"	1′ 3"	2′ 6"	0′ 10"	1′ 3"	3′ 0"	0′ 10"	1′ 3"
	3.068	1.00"	1.00"	0′ 11"	4′ 0"	1′ 2"	1′ 11"	4′ 3"	1′ 2"	1′ 11"	3′ 7"	1′ 2"	1′ 11"	3′ 9"	1′ 2"	1′ 11"	4′ 5"	1′ 3"	1′ 11"
straightening	4.026	1.00"	1.00"	1′ 2"	5′ 3"	1′ 7"	2′ 5"	5′ 7"	1′ 7"	2′ 5"	4′ 8"	1′ 7"	2′ 5"	4′ 10"	1′ 7"	2′ 5"	5′ 9"	1′ 7"	2′ 5"
vanes used	6.065	1.00"	1.00"	1′ 8"	7′ 11"	2′ 4"	3′ 8"	8′ 5"	2′ 4"	3′ 8"	7′ 0"	2′ 4"	3′ 8"	7′ 4"	2′ 4"	3′ 8"	8′ 8"	2′ 5"	3′ 8"
	8.071	1.00"	1.00"	2′ 2"	10′ 6"	3′ 1"	4′ 11"	11′ 2"	3′ 1"	4′ 11"	9′ 3"	3′ 1"	4′ 11"	9′ 9"	3′ 1"	4′ 11"	11′ 6"	3′ 2"	4′ 11"
Maximum ratio	10.19	1.00"	1.00"	2′ 8"	13′ 2"	3′ 10"	6′ 2"	14′ 1"	3′ 10"	6′ 2"	11′ 8"	3′ 10"	6′ 2"	12′ 3"	3′ 10"	6′ 2"	14′ 6"	4′ 0"	6′ 2"
(d/D)=0.75	12.09	1.00"	1.00"	3′ 2"	15′ 8"	4′ 7"	7′ 4"	16′ 8"	4′ 7"	7′ 4"	13′ 10"	4′ 7"	7′ 4"	14′ 7"	4′ 7"	7′ 4"	17′ 2"	4′ 9"	7′ 4"
	15.25	1.00"	1.00"	3′ 11"	19′ 9"	5′ 9"	9′ 2"	21′ 0"	5′ 9"	9′ 2"	17′ 5"	5′ 9"	9′ 2"	18′ 4"	5′ 9"	9′ 2"	21′ 8"	6′ 0"	9′ 2"
	19.182	1.00"	1.00"	4′ 11"	24′ 10"	7′ 3"	11′ 7"	28′ 5"	7′ 3"	11′ 7"	21′ 11"	7′ 3"	11′ 7"	23′ 1"	7′ 3"	11′ 7"	27′ 3"	7′ 7"	11′ 7"
III	D	l_1	l_2	E	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
		2.50 D	8.00 D	11.0 D	14.2 D	12.3 D		15.7 D	12.3 D		20.5 D	12.3 D		32.8 D	12.3 D		40.4 D	12.3 D	
Pipe taps	2.067	0′ 5.17"	1′ 4.54"	1′ 11"	2′ 6"	2′ 2"		2′ 9"	2′ 2"		3′ 7"	2′ 2"		5′ 8"	2′ 2"		7′ 0"	2′ 2"	
	3.068	0′ 7.67"	2′ 0.54"	2′ 10"	3′ 8"	3′ 2"		4′ 1"	3′ 2"		5′ 3"	3′ 2"		8′ 5"	3′ 2"		10′ 4"	3′ 2"	
no straightening	4.026	0′ 10.07"	2′ 8.21"	3′ 9"	4′ 10"	4′ 2"		5′ 4"	4′ 2"		6′ 11"	4′ 2"		11′ 1"	4′ 2"		13′ 7"	4′ 2"	
vanes used	6.065	1′ 3.16"	4′ 0.52"	5′ 7"	7′ 3"	6′ 3"		8′ 0"	6′ 3"		10′ 5"	6′ 3"		16′ 7"	6′ 3"		20′ 6"	6′ 3"	
	8.071	1′ 8.18"	5′ 4.57"	7′ 5"	9′ 7"	8′ 4"		10′ 7"	8′ 4"		13′ 10"	8′ 4"		22′ 1"	8′ 4"		27′ 3"	8′ 4"	
maximum ratio	10.19	2′ 1.48"	6′ 9.52"	9′ 5"	12′ 1"	10′ 6"		13′ 4"	10′ 6"		17′ 5"	10′ 6"		27′ 11"	10′ 6"		34′ 4"	10′ 6"	
(d/D)=0.70	12.09	2′ 6.23"	8′ 0.72"	11′ 1"	14′ 4"	12′ 5"		15′ 10"	12′ 5"		20′ 8"	12′ 5"		33′ 1"	12′ 5"		40′ 9"	12′ 5"	
	15.25	3′ 2.13"	10′ 2.00"	14′ 0"	18′ 1"	15′ 8"		20′ 0"	15′ 8"		26′ 1"	15′ 8"		41′ 9"	15′ 8"		51′ 3"	15′ 8"	
	19.182	3′ 11.96"	12′ 9.46"	17′ 8"	22′ 9"	19′ 8"		25′ 2"	19′ 8"		32′ 10"	19′ 8"		52′ 6"	19′ 8"		64′ 7"	19′ 8"	
IV	D	l_1	l_2	E	A′	B	C	A′	B	C	A′	B	C	A′	B	C	A′	B	C
		2.50 D	8.0 D	11.0 D	16.2 D	12.3 D	8.7 D	15.7 D	12.3 D	8.7 D	14.2 D	12.3 D	8.7 D	15.0 D	12.3 D	8.7 D	17.0 D	12.3 D	8.7 D
Pipe taps	2.067	0′ 5.17"	1′ 4.54"	1′ 11"	2′ 10"	2′ 2"	1′ 6"	2′ 9"	2′ 2"	1′ 6"	2′ 6"	2′ 2"	1′ 6"	2′ 7"	2′ 2"	1′ 6"	3′ 0"	2′ 2"	1′ 6"
	3.068	0′ 7.67"	2′ 0.54"	2′ 10"	4′ 2"	3′ 2"	2′ 3"	4′ 1"	3′ 2"	2′ 3"	3′ 8"	3′ 2"	2′ 3"	3′ 11"	3′ 2"	2′ 3"	4′ 5"	3′ 2"	2′ 3"
straightening	4.026	0′ 10.07"	2′ 8.21"	3′ 9"	5′ 6"	4′ 2"	3′ 0"	5′ 4"	4′ 2"	3′ 0"	4′ 10"	4′ 2"	3′ 0"	5′ 1"	4′ 2"	3′ 0"	5′ 9"	4 2"	3 0"
vanes used	6.065	1′ 3.16"	4′ 0.52"	5′ 7"	8′ 3"	6′ 3"	4′ 5"	8′ 0"	6′ 3"	4′ 5"	7′ 3"	6′ 3"	4′ 5"	7′ 7"	6′ 3"	4′ 5"	8′ 8"	6′ 3"	4′ 5"
	8.071	1′ 8.18"	5′ 4.57"	7′ 5"	10′ 11"	8′ 4"	5′ 11"	10′ 7"	8′ 4"	5′ 11"	9′ 7"	8′ 4"	5′ 11"	10′ 2"	8′ 4"	5′ 11"	11′ 6"	8′ 4"	5′ 11"
maximum ratio	10.19	2′ 1.48"	6′ 9.52"	9′ 5"	13′ 10"	10′ 6"	7′ 5"	13′ 4"	,0′ 6"	7′ 5"	12′ 1"	10′ 6"	7′ 5"	12′ 9"	10′ 6"	7′ 5"	14′ 6"	10′ 6"	7′ 5"
(d/D)=0.70	12.09	2′ 6.23"	8′ 0.72"	11′ 1"	16′ 4"	12′ 5"	8′ 10"	15′ 10"	12′ 5"	8′ 10"	14′ 4"	12′ 5"	8′ 10"	,5′ 2"	12′ 5"	8′ 10"	17′ 2"	12′ 5"	8′ 10"
	15.25	3′ 2.13"	10′ 2.00"	14′ 0"	20′ 8"	15′ 8"	11′ 1"	20′ 0"	15′ 8"	11′ 1"	18′ 1"	15′ 8"	11′ 1"	19′ 1"	15′ 8"	11′ 1"	21′ 8"	15′ 8"	11′ 1"
	19.182	3′ 11.96"	12′ 9.46"	17′ 8"	25′ 11"	19′ 8"	13′ 11"	25′ 2"	19′ 8"	,3′ 11"	22′ 9"	19′ 8"	13′ 11"	24′ 0"	19′ 8"	13′ 11"	27′ 3"	19′ 8"	13′ 11"

Note: l_1 is measured from the center of upstream tap to the upstream face of orifice plate.
l_2 is measured from the center of downstream tap to the downstream face of orifice plate.

Where a control valve, regulator, etc., exists upstream from the orifice and the pipe line between the fitting and the orifice is not straight the total length of irregular pipe as specified for straight pipe in Case 5 will be ample. In this case the length of straight pipe directly upstream from the orifice will then be determined by the type of pipe fitting or flow conditions just prior to the orifice.

In case of swedges, upstream, the straightening vane can be placed in the pipe just upstream from the swedge. This will be equivalent to conditions I and III and not to II and IV.

Fig. 1b



Nominal size of meter run	Standard internal dia. meter tube	Lb. per ft.	Specifications calibrated pipe: Allowable tolerance in (D) the inside diameter of pipe — Upstream section E Min. dia.	Upstream section E Max. dia.	Downstream section B Min. dia.	Downstream section B Max. dia.	Minimum lengths: Total length straight pipe upstream	Total length straight calibrated pipe downstream	Total length straight calibrated pipe upstream	Additional length of straight uncalibrated pipe required when minimum length of (E) is used	Distance to sampling connection	Location of drain valve
	D		Min. dia.	Max. dia.	Min. dia.	Max. dia.	A	B	E	G	H	I
2	2.067	3.65	2.062	2.072	2.057	2.077	12′	3′	4′	8′	1′–6″	3′
3	3.068	7.57	3.060	3.076	3.053	3.083	18′	3′	6′	12′	1′–6″	5′
4	4.026	10.79	4.016	4.036	4.006	4.046	23′	4′	7′	16′	2′–6″	6′
6	6.065	18.97	6.050	6.080	6.035	6.095	35′	4′	10′	25′	2′–9″	8′
8	8.071	24.69	8.051	8.091	8.031	8.111	46′	5′	14′	32′	3′–6″	10′
10	10.190	31.20	10.164	10.215	10.139	10.241	58′	6′	17′	41′	4′–6″	12′
12	12.090	43.77	12.060	12.120	12.030	12.150	69′	7′	20′	49′	5′–6″	15′
16	15.250	62.57	15.212	15.288	15.174	15.326	87′	8′	26′	61′	6′–6″	20′
20	19.180	85.57	19.132	19.288	19.084	19.276	110′	10′	32′	78′	8′–6″	25′

*Pipe used for Sections B and E should be seamless and calibrated as specified to above tolerances in inside diameters.

**Pipe used to make up Section G should be kept straight in line with Section E but it may have any internal diameter corresponding to any pipe having same nominal size as meter tube.

Pipe should be screwed up completely through flanges and protruding section machined off flush with raised face of flange.

Gaskets should be of materials which are unaffected by fluid being metered (see notes under "Orifice Meter Installation" instructions under Section "Orifice Meter Installation Procedure.")

For pipe taps, increase lengths A and B by distance between taps.

the present possibilities of war emergencies on the West Coast. For this reason, at least one auxiliary source of control "air" or gas should be provided to cut in automatically when necessary. The motor valves controlling the exit of oil, gas, or gasoline fractions from the various pressure vessels in the plant, could be of the normally closed type that will shut in the vessel if control air goes off and prevent the loss of inflammable material within the plant yard. Although it may be deemed advisable to provide lines that will automatically vent the contents of pressure vessels to some location outside the plant in case of emergency. It is further recommended that some sort of remote control system be provided at the plant exits so that the boilers, compressors, and heaters may be shut down by the operator in case an accident occurs that might result in a fire if these sources of ignition were present.

Wet Gas Measurement

In discussing the individual problems of measurement and control within our natural gasoline plant, let us assume that the field produces high-pressure wet gas, low-pressure wet gas, and vapors from oil storage tanks. This means that three gathering systems will be maintained and that the low-pressure gas and vapors will be compressed to a higher pressure for absorption of their gasoline fractions. It is desirable that the gas entering our medium pressure gasoline plant, from each system, be metered so that a better check between field and plant volumes may be obtained. Although it is customary for a calculated wet gas figure (based on dry gas and vapors and the shrinkage volume) to be used as a check on the total of the individual wet field meters, the master plant wet gas meters serve as an additional balance check and are very useful as operating guides within the plant. In order that the wet gas may be accurately measured by the orifice meter, it is necessary that all line condensate and oil are removed before the gas enters the meter run. For this purpose it is customary to install drip pots or a scrubber to remove the liquid before measurement. When an accumulator is used its approximate size can be computed from the following formula as given by Mr. West:

$$D = \sqrt{\frac{c}{800\sqrt{P}}}$$

When:

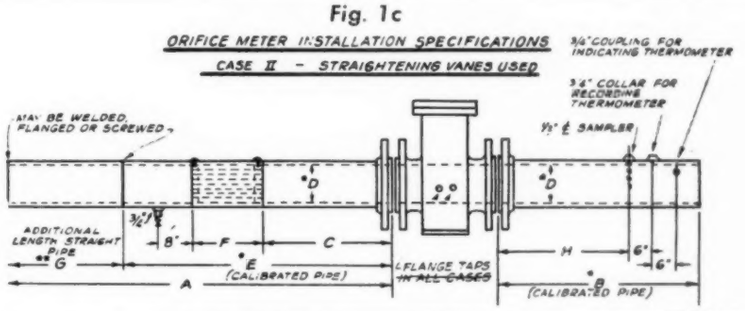
D = diameter of vessel, in.,

c = cu. ft. of gas per day, and

P = abs. pressure = lb. per in.^{2}

The length should be approximately three times the diameter for best results with inlet and outlet located near

Fig. 1c



Nominal size of meter run	Standard internal dia. meter tube	Lb. per ft.	Specifications calibrated pipe: Allowable tolerance in (D) the inside diameter of pipe — Upstream section E Min. dia.	Upstream section E Max. dia.	Downstream section B Min. dia.	Downstream section B Max. dia.	Minimum lengths: Total length straight pipe upstream	Total length straight calibrated pipe downstream	Distance to straightening vane	Total length straight calibrated pipe upstream	Length of straightening vane	Additional length of straight uncalibrated pipe required when minimum length of (E) is used	Distance to sampling connection
	D		Min. dia.	Max. dia.	Min. dia.	Max. dia.	A	B	C	E	F	G	H
2	2.067	3.65	2.062	2.072	2.057	2.077	5′	3′	2′	3′	6′	2′	1′–6″
3	3.068	7.57	3.060	3.076	3.053	3.083	8′	3′	2′	4′	8″	4′	1′–6″
4	4.026	10.79	4.016	4.036	4.006	4.046	10′	4′	3′	5′	10″	5′	2′–6″
6	6.065	18.97	6.050	6.080	6.035	6.095	15′	4′	4′	8′	15″	7′	2′–9″
8	8.071	24.69	8.051	8.091	8.031	8.111	20′	5′	5½′	10′	20″	10′	3′–6″
10	10.190	31.20	10.164	10.215	10.139	10.241	25′	6′	7′	13′	24″	12′	4′–6″
12	12.090	43.77	12.060	12.120	12.030	12.150	29′	7′	8′	15′	30″	14′	5′–6″
16	15.250	62.57	15.212	19.288	15.174	15.326	37′	8′	10′	19′	38″	18′	6′–6″
20	19.180	85.57	19.132	19.288	19.084	19.276	46′	10′	13′	24′	60″	22′	8′–6″

*Pipe used for Sections B and E should be seamless and calibrated as specified above tolerances in inside diameter.

**Pipe used to make up Section G should be kept straight in line with Section E but it may have any internal diameter corresponding to any pipe having same nominal diameter as meter tube.

Pipe should be screwed up completely through flange and protruding section machined off flush with raised face of flange.

Gaskets should be of materials which are unaffected by fluid being metered (see notes under "Orifice Meter Installations" instructions under section "Orifice Meter Installation Procedure.")

FIG. 1d

Specifications for orifice fittings

Nominal size, in.	Standard bore as per C.N.G.A. Bulletin TS-353	BORE SPECIFICATIONS: in bore ± 00.2 Allowable variation percent	
3	3.068	3.062	3.074
4	4.026	4.018	4.034
6	6.065	6.053	6.077
8	8.071	8.055	8.087
10	10.19	10.170	10.210
12	12.09	12.066	12.114
14	13.25	13.224	13.276
16	15.25	15.220	15.280
18	17.18	17.146	17.214
20	19.18	19.142	19.218
24	23.25	23.204	23.296

Bore should be machined to as near the standard bore as possible. Average bore should be stamped on top of flange of fitting.

Orifice fittings having no defects in the bore of the fitting such as pits, scratches, etc., and which have bores within the allowable limits specified shall be acceptable unless otherwise specified.

Bores should be checked across the vertical and horizontal diameters at 1 in. in from each face of fitting, and at 1 in. from both sides of slot for orifice plates.

Bore of fitting should be smooth and free from pits, scratches, etc. When these defects exist, they should be cleaned out and filled in with iron by means of the electric arc, and machined off smooth.

Pressure tap holes. Check pressure tap holes for leaks.

Set screws for holding orifice plate. Set screws should be carefully checked to see that they are in perfect condition and that the threads in fitting are in good condition. Set screws should be tight but they should not be so tight that they might bind.

top of each end. Provision should be made for draining the vesel of liquid.

Pulsation

Another difficulty often encountered in the measurement of wet gas and vavors when the meter is situated near the compressor suction is caused by pulsation. The pressure and velocity waves produced in the gas by the action of the reciprocating compressor cause errors in the differential reading which may amount to as much as 200 percent. By making the gauge lines leading to each side of the meter approximately the same, the error due to the pressure pulsation can be largely eliminated. The only way to insure freedom from error due to the velocity waves, however, is to damp the waves before they get to the meter run. This can be done by creating a pressure drop between the meter and compressor suction or by making the volume between these points comparatively large, or both. The relation between these factors is shown by the Hodgson equation.

$$F = \frac{0.25Q}{CR}$$

When:

F = frequency of pulsation,
Q = quantity of gas,
C = volume of piping between meter and compressors, and
R = pressure drop between meter and compressors.

Because it is important that the pressure drop in the suction to the compressor be kept to a minimum for highest compressor efficiency, it is usual practice to eliminate the pulsation by placing sufficient volume between the meter run and the compressors. This condition may be obtained by placing the meters at a distance from the compressors or by installing a scrubber or an accumulator just ahead of the compressor inlet. This same formula could be used to determine the proper location for a meter on the wet gas discharged from the compressor. Here it might be found advisable to install a regulator to maintain a pressure drop as the fractional damping of the velocity wave is much less at the higher pressures. In most cases, however, the volume represented by the high-pressure condensate scrubber will be sufficient to "cushion out" the effect of the waves.

Another formula for estimating the size of pulsation dampening tanks was given by R. E. Morter of the Industrial Fuel Supply Company in 1939.

$$V = 1500\frac{Q}{P}$$

When:

V = volume of tank in cu. ft.,
Q = flow in MCF per 24 hr., and
P = absolute pressure.

He suggests that the length of the tank be 1.75 times the diameter and that the inlet and outlet connections should be at opposite ends and 90° to each other. This design was based on experimental data and results have been very satisfactory.

It has been common practice in the past to try to eliminate the effects of pulsation by installing a bushing between the high and low pots of the orifice gauge. This should be discouraged

Fig. 1e

Orifice Plate Specifications

As determined from specifications given in C.N.G.A. Bul. TS. 353, W. L. Cowan, Feb. 12, 1936

SPECIFICATIONS BASED ON FOLLOWING REQUIREMENTS

t' must be $\frac{1}{16}$" or greater.

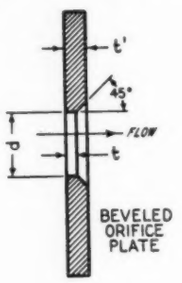
LETTING D = INTERNAL DIAM. OF PIPE

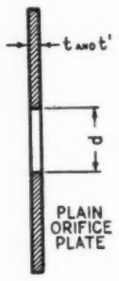
t = or is less than $\frac{1}{30}$D

t = ... $\frac{1}{50}$D (preferably)

t = ... $\frac{1}{8}$d

t = ... $\frac{D-d}{8}$





SPECIFICATIONS FOR t

ORIFICE DIAM. d	PIPE SIZE 2"	3"	4"	6"	8"	10" to 20"
.250"	1/32"	1/32"	1/32"			
.375"	"	3/64"	3/64"			
.500"	"	1/16"	1/16"			
.625"	"	"	"	1/16"		
.750"	"	"	"	3/32"		
.875"	"	"	"	"	3/32"	
1.000"	"	"	"	1/8"	1/8"	
FOR ALL ORIFICES GREATER THAN 1.0"	"	"	"	"	"	1/8"

SPECIFICATIONS FOR t'

t'	
PIPES	VARIATION
2" TO 4"	1/16" TO 1/8"
6" TO 12"	1/8" TO 1/4"
16" TO 20"	1/8" TO 3/8"

ADDITIONAL PLATE SPECIFICATIONS

Upstream face of plate must not depart from flatness more than .01" per inch of pipe radius, when in operation.

Upstream edge of orifice shall be cut square and sharp so that it will not appreciably reflect a beam of light when viewed without magnification.

RECOMMENDED RANGE OF β, β = d/D	Flange Taps	β From .15 to .70
	Pipe Taps	β " .20 " .67
PERMISSIBLE BUT NOT DESIRABLE RANGE OF β WHERE HIGH ACCURACY IS NOT ESSENTIAL	Flange Taps	β From .10 to .75
	Pipe Taps	β " .10 " .70

Again...

THERE GO YOUR VALVES

Pig Boats

d Tin

With a crew o
rine in Pacif
to sink twenty or
end of this war. A
men and with many
er, can count itself extr
well. The 120 to 150 men who
destroyer will be pleased if they are
a cruiser's bag. As for the 1200 men on a
ship, their chances of doing spectacular damag
to enemy craft are governed by luck. Not more than once in one war do they expect to use their killing capacity to the limit. By the nature of his ship and machine, a submariner thus rates himself as the most efficient killer in the science of naval warfare.

By its very limitations, the submarine offers its crew opportunities to do damage to the enemy which are not given sailors on other types of vessels. Ninety per cent of the time during war our pig boats are looking for the enemy. Cruisers and destroyers, on the other hand, must often pass up the privilege of fighting in order to carry out some broad strategic objective; thus convoying, reconnaissance and scouting become a kind of boresome duty the submariner seldom knows.

Like the crews of Flying Fortresses and Liberators, pig boat men are trained hair-fine for team action. To an extent impossible to sailors on cruisers and destroyers, the security and efficiency of each one is involved with that of his fellows. No submarine skipper rates himself as more valuable than the humblest Seaman 2ndC on his ship. They are a proud lot, our pig boat men, but not boastful. They talk less of their exploits than the public likes. The brasshats apparently have decided to keep it that way. Certain critics, particularly Walter Lippman, believe the strategists in Washington have a long way to go before they will be as smart on undersea warfare as the Germans; this despite the fact that the sub is an American invention.

Maybe we aren't really smart in the way we run this branch of naval warfare, but there can be little criticism of how American subs fight. Prowling the dangerous waters of the western Pacific even to the coasts of Japan they are taking terrific toll of a wily and vicious enemy. One will get you five that when the victory score is at last compiled, the pig boats will be crowding the top.

from the April issue of "Click"

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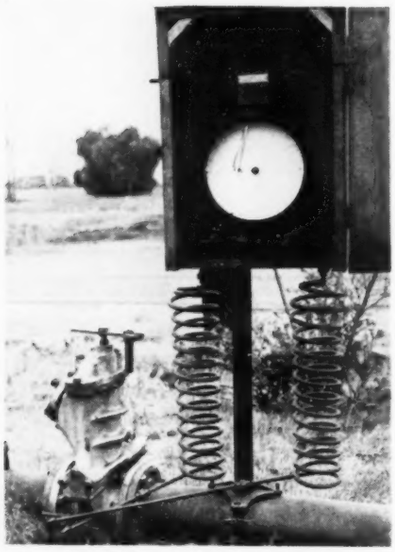

Fig. 2

as the average damped out differential seldom is the same as the average square root of the pulsatory differential which is the correct reading for determining actual flow volumes.

It may be mentioned here that care should be given the placing of the high-pressure wet gas meter. It is found in most cases that progressive pressure decline of the field will eventually necessitate the use of compressors for the proper treatment of this wet gas. When this is done it will entail the relocation of the wet gas meter to eliminate pulsation unless this meter has already been located at sufficient distance from the proposed compressor inlet.

Vapor Measurement

When the wet gas or vapors coming into the plant at low pressure are rich in gasoline content, difficulty may be experienced due to condensation of the liquid in the gauge lines of the meter, causing an erroneously high or low differential to be recorded. This condition can be alleviated by using large size gauge lines and sloping them from the meter gauge down to the meter run connection. This allows the condensate to run back into the line without forming "slugs" of liquid which would plug the line and give false differential readings. One company has used the method shown in Fig. 2 to eliminate this trouble. The gauge lines are made in the form of coils with a continuous slope downward into the main line. The opening into the line was reamed out so that the liquid condensed by the large surface area of the coil could easily run back out of the gauge lines without forming obstructions.

It is recommended that the meter runs used for the measurement of the various wet gases and vapors into the plant be of the "code" type. Although these meters are not as important as the dry gas distribution meters, their place in the checking of plant volume balances justifies the additional degree of accuracy.

Absorption System

After the measurement of the various wet gases and vapors into the plant and the extraction of the liquid condensate before and after compression they are treated in the absorbers to remove their valuable liquid constituents. Fig. 3 represents a unit of the absorption system, each one of which would be identical, the number depending upon the desired capacity of the plant. It will be seen that no measurement or control of the gas is made until it has passed through the absorber. Although some plants at present measure the individual wet gas to each absorber as well as the dry gas out, in order to check the performance of each absorber, it is not generally felt to be justified. The measurement of the gas *out* of each absorber, however, is of definite value and "code" meter installations should be made. The individual meters are used to check the volume recorded by the master dry gas meter and also serve as an indication to the operator of the amount being treated by each absorber. It is customary for the absorber dry gas meter to be placed on the vertical line from the top of the absorber to the ground and this practice is recommended as it conserves space and violates no principle of good measurement. The meter is, of course, placed at ground level and the gauge lines run upward to the meter run. Pots should be installed at the meter to prevent any liquid from accumulating in the lines.

It is important as an operating guide that individual oil meters be installed on the absorbers although they may be of the non-code type. Here again it is recommended that pots be installed at the meter so that any accumulated water in the oil may be drained from the gauge lines. The importance of these meters lies in the fact that for efficient operation, certain absorption factors must be maintained, and to do this the ratio of oil to gas must be known. As the volume rate of wet gas treated remains generally constant, the rate of oil is usually hand set by means of a pinched valve, against which the lean oil pumps maintain a constant pressure, or by hand controlling the rate of steam to the pumps.

In order that the absorption in the tower may be controlled, it is necessary that constant pressure be maintained. For this purpose a back-pressure regulator is installed on the residue gas from the absorber, and when several towers are in operation, should be placed in the master dry gas line downstream of the master dry meter. As it is desirable that the absorber pressure remain absolutely constant, regardless of rate of flow, it is recommended that a pilot operated regulator be used.

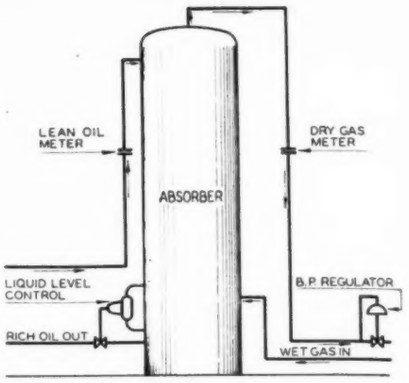

Fig. 3

A liquid-level control must be installed on each absorber to maintain the flow of rich oil from the absorber and hold an approximately constant level in the tower. Although it is possible to use the ordinary float ball type of control, directly operating a valve on the oil line, it is recommended for new installations that a controller pneumatically operating a motor valve be used. This type of control will maintain a much closer level under all flow conditions and can be better sized to suit particular needs.

All of these controls and meters will apply to the vapor absorber, when one is used to treat the various plant vapors. One further control should be added, however, because of the fact that the rate of vapors going to the absorber generally fluctuates over a wide range. It would be impossible for hand control of the oil rate to this absorber to give the desired constancy of oil-gas ratio, and so the installation of a ratio controller is recommended. This controller operates a motor valve on the lean oil line to maintain a constant ratio between the differentials recorded by the oil and gas flowmeters. By placing the vapor absorber residue gas meter upstream of the back-pressure regulator, the pressure recording is held constant and the volume ratio is maintained in direct proportion to the ratio of the differentials. Most controllers are constructed so that the ratio can be set within the instrument to any figure desired by the operator.

Dry Gas Distribution

Downstream of the master dry gas

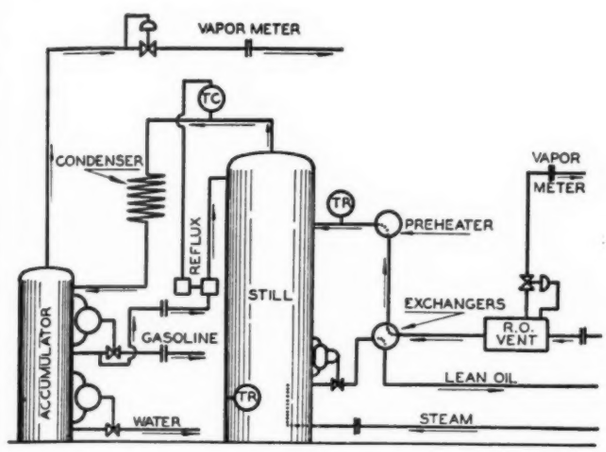

Fig. 4

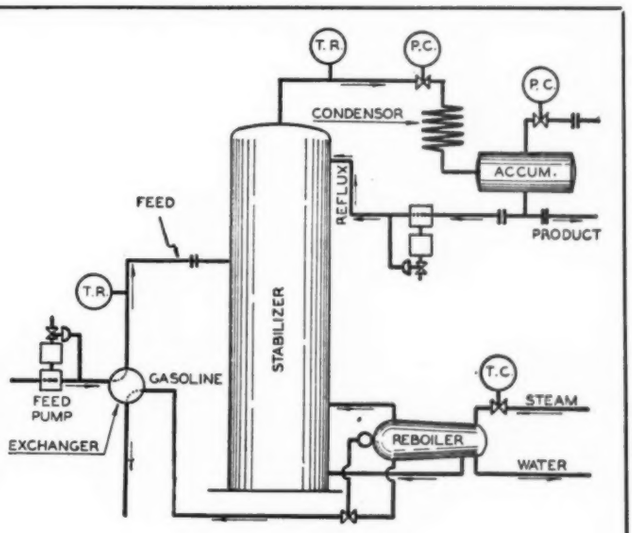

Fig. 5

regulator, the various high-pressure dry distribution meters are manifolded. These should be "code" installations. It is usual practice for the discharge of the regulator to enter a large manifold line out of which the gas is distributed. In most plants the order of precedence of these services is: first to plant fuel, next to the field fuel, third to sales, and lastly to the air stack. By maintaining proper pressure control on each line this order may be easily obtained. Each of these services should be metered using a "code" meter run and meter set-up. The regulators for the plant and field fuel lines should be direct operated reducing regulators with the pressure setting lower on the plant line. In addition, it will be necessary to install a back-pressure regulator on the field fuel line set to close as the pressure becomes lower than that necessary for plant needs if there is insufficient for both. The sales pressure usually depends on that maintained by the receiving company, although a pilot-operated back-pressure regulator should be installed to protect this plant pressure against any sudden draw-off of gas. This regulator should be set at a pressure lower than the regular sales delivery pressure but above that of the plant and field fuel. The gas to air regulator should be a pilot-operated back-pressure valve set higher than the delivery to sales pressure, but lower than the master dry out regulator.

Although this particular case will not fit all plants, similar pressure control will permit proper distribution of the gas. Care should be taken to protect the plant against sudden draw-off of gas by reason of sudden loads or line breaks. Provision should always be made for venting excess dry gas or vapors to air at a stack away from the plant.

Rich Oil Measurement

The rich or fat oil, after passing from the absorbers, is usually flashed into a vent tank in order that fixed gases may be removed before the oil enters the still. The vapors from this tank commonly enter the recycle stream and are picked up in the vacuum compressor intake. These vapors should be measured and an orifice meter set-up similar to the plant vacuum intake meter should be used. It is customary to maintain a pressure of about 5 to 10 lb. on the rich oil vent tank and a direct-operated back-pressure regulator should be set on the vapor line for this purpose. If the meter is situated downstream of the regulator, the expansion of the vapor will help prevent condensation of liquid in the meter gauge lines.

It is not entirely necessary to measure the rich oil to the still when the ratio of steam to lean oil is used for a stripping basis. Modern plant practice seems to favor the use of direct-fired preheaters, and when more than one of these are used it is advantageous for rich oil meters to be installed on each heater so that the load may be equally distributed between them. An overhead meter run is recommended for this installation using taps situated on the side of the line and vent pots for each gauge line so that any accumulated vapor may be vented off. It is not necessary for seals to be used. Where gas-fired heaters are used the fuel should be measured to them by meter so that their operating efficiencies may be checked. When vapors are used, the meter set-up will be the same as that described for plant intake vapors.

Distillation System

The plant still operates to strip the gasoline constituents from the absorption oil, which may then be cooled and stored for return to the absorber. Fig. 4 shows a representative diagrammatic sketch of the distilling unit. The pressure on the still is controlled by direct operated back-pressure regulator on the run-down vapors. These vapors should be measured by non-code meter set-up. Liquid level controls of the pneumatically operated motor valve type, are recommended for the maintaining level of oil in the still and of gasoline and water in the run-down tank.

The spray steam to the still and the preheater steam should be measured using overhead horizontal meter runs that have been preceded by steam traps. It has been found advantageous to rotate the orifice fitting so that the taps are located near the top of the line. The taps should connect over to water condensing pots and gauge lines run down to the meter. The steam meters may be non-code in construction.

A non-code meter run set-up may be used for the measurement of the reflux to the still, although it is possible for positive meters to be installed for this purpose. The reflux rate must be controlled in order that a uniform overhead product may be obtained. This is accomplished by maintaining the top temperature constant. A recording temperature controller should be installed with its actuating element placed in the overhead line from the still. The instrument should be connected to operate a steam motor valve that will control the reflux pumps and insure the proper amount of cooling medium to the still. A temperature recorder should be set up for recording the bottom temperature of the still, as this must be used as an operating guide for the efficient stripping of the oil. By combining the operation of the various still meters and controllers with infor-

mation obtained by testing the products, a high quality "raw" gasoline of uniform characteristics may be produced.

Storage of Gasoline

If no further stabilization of the gasoline is desired, the product is taken from the run-down tank into storage tanks to await shipment or use. The vessel used for gasoline storage should be protected by safety valves and vacuum breakers to prevent over or under pressuring the tank. The vapors that may be given off from the tanks should be controlled by a direct-operated back-pressure regulator, and should be measured by a noncode meter set-up back into the plant vapor recycle system. It may be found advantageous to install a remote liquid-level recorder in the plant control house to indicate the level of the gasoline in the storage tanks.

Rectification or Fractionation

When rectification of the raw gasoline is desired, a unit or units similar to that shown in Fig. 5 may be used. With the current demand for *iso*butane as alkylation stock and propane and normal butane for liquefied fuel, it is economically profitable to progressively separate these constituents in a series of fractionating units. The measurements of the various liquid products and control streams in this section of plant operation may be accomplished by the use of positive meters. The difficulty of measuring these volatile products by orifice meter is due to the tendency of the liquid to vaporize in the lead lines, causing large errors in the gauge reading. The accuracy obtained by the positive meters is in general higher than that possible with the orifice meter.

The accurate control of temperature and pressure on the fractionating columns is more necessary for the production of these fractions than for any other plant operation. Any reasonable expense incurred for the purpose of maintaining the closest possible accuracy will be more than repaid in the salability of the refined products.

The pressure of the fractionating units should be maintained with back-pressure motor valves situated on the vapor line off the accumulator and actuated by a recording pressure controller, which may be placed in a central control house. Meters should be provided for measuring the feed and reflux rates and also for the various products off the fractionating units. The uncondensed vapors should be measured by an orifice meter so that a complete volume balance of products in and out may be kept.

The temperature of the bottom of the column is maintained by a controller-recorder whose actuating bulb should be situated either in the reboiler or in the lower part of the column. The selection of this control point should be made with the thought in mind that the quality of the bottom product will depend on holding the bottom temperature constant and also that the point of change of maximum temperature change with process changes will give the closest control. The top temperature, which determines the type of top product removed, should be controlled by the same type of instrument.

Water measurement, when it is required for accounting purposes, should be made with a positive meter. When it is made for operating purposes, measurement by weir is sufficiently accurate. The weir can usually be installed in the suction pit of the basin.

Maintenance of water levels in cooling tower basins may be provided by pneumatically operated float controllers. Other auxiliary equipment should be investigated to provide automatic control wherever possible and profitable.

When it is necessary to use sealing pots and water seals in the gauge lines between the meter run and the gauge, difficulty may be experienced in the winter because of the freezing of the water. This difficulty may be overcome by adding anti-freeze solution such as glycol or glycerine. It should be noted that if this is done, a special sealing factor will have to be used in calculating the orifice meter coefficient, based on the density of the mixture.

As a concluding theme, it should be remembered that the successful operation of any natural gasoline plant depends to a large extent on two factors: first, a sound basic design for plant equipment and second, the operation of the finished plant at highest possible efficiency. The place of measurement and control in the fulfillment of these points is of greatest importance to the operator and should be given careful consideration.

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2. "Pulsating Flow of Gas in Orifice Meters", Robert E. Morter, *Southern California Meter Association Publication No. 3*, October 26, 1939.

☆ ☆ ☆

Future Cars to Be Small and Light, Consuming High-Octane Gasolines

Post-war automobiles will be small, light-weight editions fueled by high-octane, heavily-taxed gasolines now available only for military aircraft and motorized equipment. Post-war manufacture of 100-plus octane gasolines will force engineers to design Diesel engines that will get the utmost out of low-cetane fuels for railroad, marine, long-distance and overseas air cargo, and construction service.

This prediction for the post-war petroleum fuels situation was placed before the Diesel Engine and Fuels and Lubricants Meeting of the Society of Automotive Engineers in Cleveland, Ohio, recently by Dr. C. M. Larson, chief consulting engineer, Sinclair Refining Company, New York City. He reported that high-octane aviation gasolines, explosives, synthetic rubbers, plastics, anaesthetics, and other essential war products now are being made in petroleum refineries at the expense of the kerosines and distillates from which Diesel fuels are derived. He expressed the opinion that Diesel fuels will be on the critical list by 1944 and said that even after the war the extremes between octanes for gasoline engines and cetanes for Diesel engines will broaden in favor of high octanes to the detriment of Diesel fuel ignition quality.

Dr. Larson's post-war picture indicated that premium grade gasolines will be 87- to 90-octane, regular grades 80-octane, and third grades 72- to 75-octane. Tractor or distillate fuels of 50-octane, 40-cetane, will be available, but in many regions tractor distillate fuels will have to be used with 37-40 cetane, or cetane additive agents will be employed to maintain the 50-cetane minimum called for by manufacturers of high-speed Diesel engines.

He warned that the current demand for distillate fuels by the armed forces, particularly the Navy, will reduce the potential of Diesel fuels and heating oils. He estimated the 1945 production ratio of gasoline to distillate fuel at seven to one as compared with three to one at the beginning of World War II.

Crude Naphtha Stabilizer Performance *

By

J. Q. McGIFFEN

Standard Oil Company of Ohio (Latonia Refining Corp., Latonia, Kentucky)

Abstract

EXPERIMENTAL data recently obtained from six different engineering performance tests run on a 42-in. I.D. by 61 ft., 30-tray crude naphtha stabilizer have been evaluated and are reported under three different headings. These are:

1. Tower performance
2. Exchanger performance
3. Podbielniak analyses and laboratory inspections

A schematic flowplan of the tower and exchanger equipment, and a layout of the stabilizer plate and tower details are given. An isometric drawing of the plant, and a photograph of the equipment are also included.

The tower was operated just below flooding conditions during the test periods to make as close a cut as possible between *iso* and normal pentane, and normal butane and *iso*pentane, from a feedstock consisting of raw straight-run crude naphtha. Results obtained indicate that tower performance suffers when so-called critical or limiting vapor velocities and safe downcomer velocities are reached. Safe downcomer velocities are shown to be as high as 1.5 ft. per second in some cases. At high velocities the heat transfer coefficients of the exchanger equipment were increased.

Introduction

The information and data contained in this paper is being released and published in the hope that it will stimulate discussion and interest in the subject of critical vapor and downcomer velocities in commercial bell-cap plate fractionating towers. Very little information is available in the literature at present on this subject and full-scale plant data on such equipment is ordinarily withheld.

Numerous ideas have been advanced in the literature, however, pertaining to critical velocity conditions and entrainment in laboratory and semi-plant scale columns, with some correlations between these data and column design and commercial towers performance. This literature includes articles by the following: Souders and Brown,[1] Rogers and Thiele,[2] Holbrook and Baker,[3] Ashraf et al.,[4] Rhodes,[5] Sherwood and Jenny,[6] Pyott et al.,[7] and Harbert et al.[8]

This paper reports plant data and calculated results on six full-scale engineering tests recently conducted on a complete crude naphtha stabilizer system. The calculated results for each test include the following:

I. Internal reflux at top of tower
II. Limiting vapor velocity in free area at top of tower
III. Actual vapor velocity at top of tower (free area and slots)
IV. Downcomer velocity at top of tower
V. Vaporization in reboiler
VI. Limiting vapor velocity in free area at bottom of tower

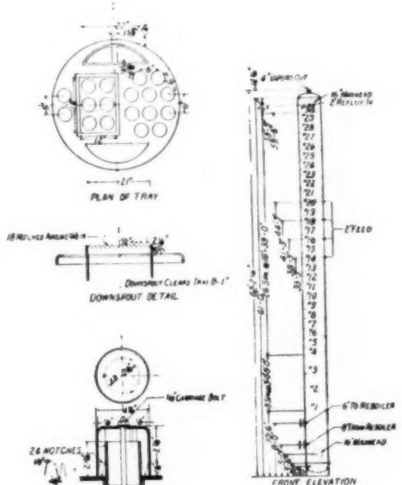


Fig. 1. Crude naphtha stabilizer details

VII. Actual vapor velocity at bottom of tower (free area and slots)
VIII. Downcomer velocity at bottom of tower
IX. Tower performance—percent separation obtained
X. Heat exchanger performance

Illustrative calculations for Test VI have been included for the first eight points above under "Method of Calculation of Results."

Crude Naphtha Stabilizer

The stabilizer tested had an inside diameter of 42 in. and an overall height of 61 ft., with a total of 30 trays. Tray spacing was 18 in. for 27 trays, with a 3-ft. spacing for the bottom three trays. Tower, tray and cap details are shown in Fig. 1. Each tray contained 18 bell caps, 4-7/16 in. O.D. An added feature of the tower was a 12-in. by 18-in. rectangular bolted section in every plate, which provided a system of interior manways up through the tower, starting from the bottom. Downcomers were of the half-moon type, with notched circular weirs, with the bottom of each downcomer having a 1-in. clearance from the top of the tray below. The following pertinent areas were used for velocity calculations:

1. Free tower area for vapor velocity (Note that this is the difference between the total free area of the tower equal to 9.61 sq. ft. and the total area of one downcomer equal to 0.61 sq. ft.)—9.0 sq. ft.
2. Total slot area per tray—1.055 sq. ft.
3. Limiting area at top of downcomer—0.444 sq. ft.
4. Limiting area under downcomer —0.357 sq. ft.

The feed to the tower, shown in a flow diagram in Fig. 2, was pumped by a simplex reciprocating steam pump taking suction on a 10 by 30 ft. feed drum. It flowed countercurrent through the tube side of two bottoms-feed tube and shell type heat exchangers and from thence into the tower on tray No. 16 (from the bottom). The stabilized bottoms after leaving the feed exchangers flowed through a cooler, with water in the tube side, and from there to the tank field. Reboiler heat was supplied by steam, average pressure equal to 135 lb. per sq. in., in the tubes of the reboiler exchanger. Totally condensed overhead after leaving the two overhead condensers, with cooling water in the tubes, was delivered to the reflux accumulator, and reflux returned to the tower by means of a simplex reciprocating steam pump. Excess overhead liquid production was delivered to another plant nearby. The tower was equipped for operation with a back-pressure control valve on the uncondensed gas line leaving the system. However, the tower was operated during the first four tests with this line shut off, and the pressure was then maintained by controlling the temperature of the totally condensed overhead by adjusting the water rate. The last two tests were also run with totally condensed overheads. A new pressure control valve system, which maintained a steady pressure on the reflux drum by bypassing hot vapors around the condensers into the reflux drum as the pressure dropped, was successfully used during these last two tests. Fig. 3 gives an isometric layout of the entire crude naphtha stabilizer system, and

*Presented before American Institute of Chemical Engineers, Boston, Massacusetts, May 11-13, 1942.

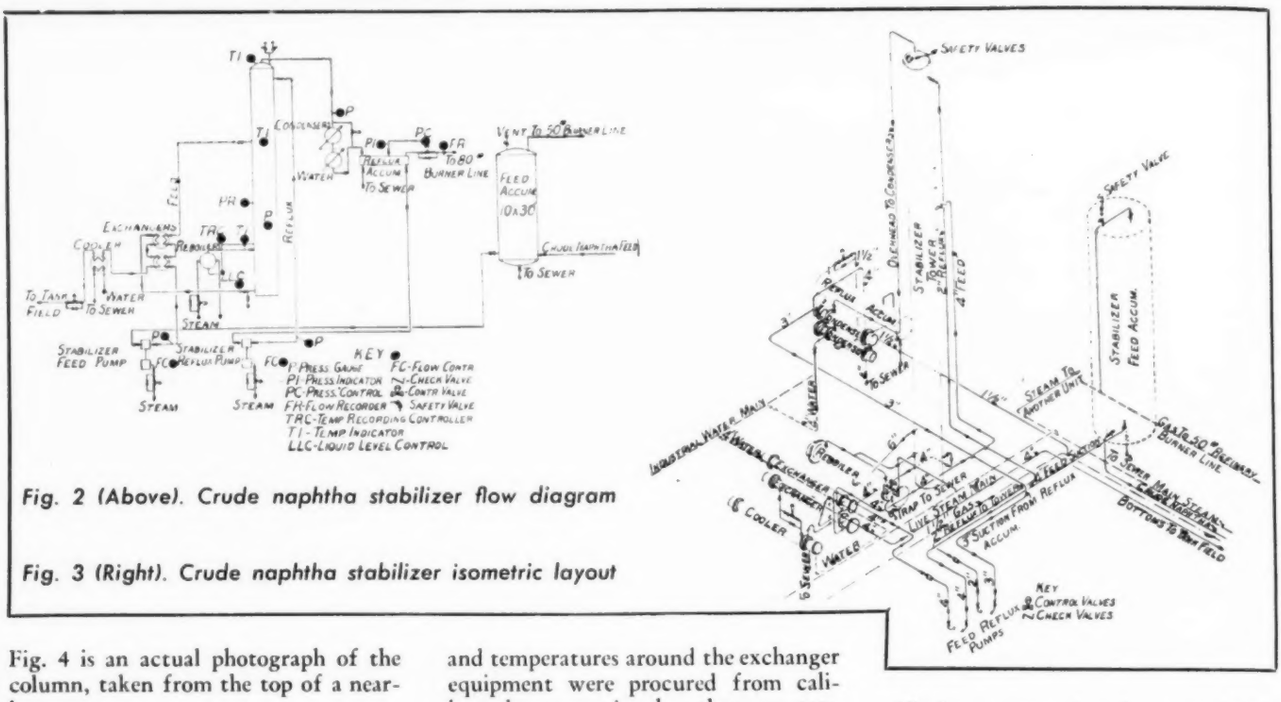


Fig. 2 (Above). Crude naphtha stabilizer flow diagram

Fig. 3 (Right). Crude naphtha stabilizer isometric layout

Fig. 4 is an actual photograph of the column, taken from the top of a nearby tower.

Test Procedure

Six separate tests were run on the system. The first four were run during winter and the last two under summer conditions. Tests I, II, V, and VI were performed attempting to cut between *iso*pentane and normal pentane overhead, whereas during Tests III and IV an attempt was made to cut between normal butane and *iso*pentane. The tower was operated during all six tests in such a manner as to produce nearly flooding conditions. In each case the tower was actually flooded, evidenced by tower center and top temperature rising and approaching each other, by the reflux drum level rapidly rising, and by the overall pressure drop between reflux drum and tower bottom becoming excessive. The tower was then backed down (reflux rate lowered or reboiler temperature reduced) slightly from these conditions for each test and allowed to reach equilibrium over a period of several hours, at the end of which time complete test data and samples were taken. The extent of this "backing down" effect naturally varied from test to test, but for all cases the operating conditions can be considered as next door to flooding.

Test data were taken from existing tower equipment, shown in Fig. 2. Additional test information was obtained by means of indicating pressure gauges, and temperatures around the exchanger equipment were procured from calibrated mercury in glass thermometers. Stabilized bottoms production was obtained from tank gauges and liquid overhead production was calculated by difference between feed rate measured with a recording flow control meter and bottoms production.

Samples of stabilized bottoms, and liquid overhead production were taken into special pressure sample bombs for Podbielniak analysis and complete laboratory inspections. A Podbielniak heligridpacked column of the automatic type was used. Laboratory inspection data are reported on a feed sample covering the first four tests, and on individual feed samples for the last two tests.

Calculation of Results

In order to facilitate interpretation of the data, the following sample calculation of Test VI is offered. A similar procedure was followed in the calculation of the first five tests. Although no examples of exchanger heat transfer coefficient calculations are shown, the standard method of calculation was followed throughout.

Rates

Feed	30,200 lb. per hr.	5.665 lb. per gal.	76.4°A.P.I.
Bottoms	26,050 lb. per hr.	5.837 lb. per gal.	70.3°A.P.I.
Overhead production	4,150 lb. per hr.	4.74 lb. per gal.	117.2°A.P.I.
Reflux	8,460 lb. per hr.	4.74 lb. per gal.	117.2°A.P.I.

*Properties**

Feed, 168°F. mid-boiling point. Characterization factor = 12.6. Specific heat correction factor = 1.045.

Bottoms, 171°F., mid-boiling point. Characterization factor = 12.2. Specific heat correction factor = 1.022. Molecular weight = 89. Latent heat at atmospheric pressure = 144 B.t.u. per lb. Latent heat at 104.5 lb. per sq. in. absolute pressure = 109 B.t.u. per lb.

Overhead production and reflux, 10°F. mid-boiling point. Molecular weight = 58. Average composition = *iso*butane.

I. Calculation of internal reflux at top of tower.

Heat out in overhead condensers. (Total heats from Sage and Lacey.[12])

(In) Total heat of IC_4H_{10} above 60°F. at 147°F. and 110 lb. per sq. in. absolute = 175.5 B.t.u.per lb.

(Out) Total heat of IC_4H_{10} above 60°F. at 102°F. and 110 lb. per sq. in. absolute = 24.0 B.t.u. per lb.

Difference = 151.5 B.t.u. per lb.

(Overhead product) + (external reflux) = (total overhead product)

4,150 lb. per hr. + 8,460 lb. per hr. = 12,610 lb. per hr.

12,610 (151.5) = 1,912,000 B.t.u. per hr.

Referring to Fig. 5, a heat balance envelope was drawn around the top plate and overhead condensing system, with nomenclature as follows:

P_V = Heat entering in overhead production vapors above 60°F. at 154°F. and 113 lb. per sq. in. absolute in B.t.u. per hr.

P_L = Heat leaving in overhead production liquid above 60°F. at 102°F. and 108 lb. per sq. in. absolute in B.t.u.per hr.

R_V = Heat entering in internal reflux vapors above 60°F. at 154°F. and 113 lb. per sq. in. absolute in B.t.u. per hr.

R_L = Heat leaving in internal reflux liquid above 60°F. at 154°F. and

*Characterization factor data, specific heats of liquids, specific heat correction factor, mid-boiling point, molecular weight, latent heat at atmospheric pressure—Watson and Nelson,[9] and Watson, Nelson and Murphy.[10] Latent heat change with pressure—Watson.[11]

113 lb. per sq. in. absolute in B.t.u. per hr.

H = Total heat leaving in overhead condensers above 60°F. at 110 lb. per sq. in. absolute in B.t.u. per hr.

R = Internal reflux in lb. per hr.

h_R = Latent heat of R at 154°F. and 113 lb. per sq. in. absolute in B.t.u. per lb.

Then, equating:

$$P_V + R_V = R_L + H + P_L \quad . \quad (1)$$

$$R_V - R_L = H + P_L - P_V \quad . \quad (2)$$

$$R = \frac{R_V - R_L}{h_R} \quad . \quad . \quad . \quad (3)$$

The quality of overhead product vapor and liquid, and internal reflux was considered to be *iso*butane. The heat data used below was obtained from Sage and Lacey.[12]

P_V = 4150 (lb. per hr.) × 177.5 (total heat in B.t.u. per lb. = 737,500 B.t.u. per hr.

P_L = 4150 (lb. per hr.) × 24 (total heat in B.t.u. per lb.) = 99,600 B.t.u. per hr.

H = 1,912,000 B.t.u. per hr.

h_R = 120.5 B.t.u. per lb.

Solving equations (1), (2) and (3): R = 10,580 lb. per hr.

Internal weight reflux to overhead product ratio at top of tower

$$= \frac{10{,}580}{4{,}150} = 2.55 \text{ per } 1.$$

II. Calculation of limiting vapor velocity in free area at top of tower.

This velocity was determined using the following formula:

$$V_c = 4.04 \sqrt{\frac{TS}{MP}}$$

Where:

V_c = critical vapor velocity in ft. per sec. based on entrainment droplet = 0.004 in.,

T = vapor temperature in °R,

S = liquid specific gravity at temperature, T,

M = vapor molecular weight,

P = operating pressure, in lb. per sq. in. absolute, and

4.04 = factor for maximum velocity with high fractionating efficiency for 18-in. tray spacing.

This formula is similar to that reported by Packie,[13] except that he used P in terms of inches of Hg absolute, giving a slightly higher factor, i.e., 6.65. Packie's factor becomes 4.66 when P is expressed in lb. per sq. in. absolute, although his equation is applicable to crude distillation equipment, whereas the equation expressed above has been developed for gasoline distillation equipment.

Solving the preceding equation, where

T = 154 + 460 = 614°R,

S = 0.493 at 154°F.,

M = 58,

P = 113 lb. per sq. in. absolute,

gave V_c = 0.87 ft. per sec.

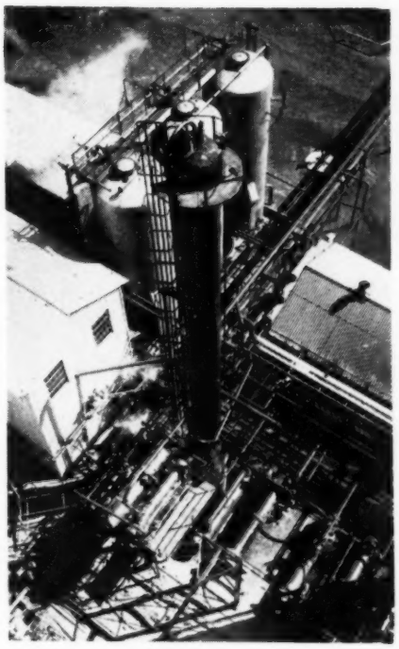


Fig. 4. Crude naphtha stabilizer system

III. Calculation of actual vapor velocity at top of tower.

$$\text{Vapor volume} = \frac{\text{Total overhead}}{\text{Molecular weight}} = \frac{12{,}610 \text{ lb. per hr.}}{58} = 217 \text{ lb. moles per hr. at standard conditions.}$$

This was corrected to conditions at the top of the tower as follows: (Refer to Fig. 5.)

Pseudo critical pressure = 530 lb. per sq. in. absolute (Smith and Watson[14]).

$$\text{Reduced pressure} = \frac{113}{530} = 0.21.$$

Pseudo critical temperature = 735°R Smith and Watson[14]).

$$\text{Reduced temperature} = \frac{614}{735} = 0.84.$$

From reduced pressure and reduced temperature data prepared by Lewis,[15] the compressibility factor μ was determined to be equal to 0.833. This was used to correct the actual vapor volume for deviations from the perfect gas laws as follows:

$$\text{Vapor volume} = 217 \times 0.833 \times \frac{14.7}{113} \times \frac{614}{520} \times \frac{379}{3600} =$$

2.93 cu. ft. per sec. (corrected)

$$\text{Vapor velocity} = \frac{2.93}{9.0} = 0.33 \text{ ft.}$$

per sec. in free area of tower at top

$$\text{Vapor velocity} = \frac{2.93}{1.055} = 2.78 \text{ ft.}$$

per sec. in slots on top plate

From the above it can be seen that the free area vapor velocity at the top of the tower was considerably under the critical condition for Test VI.

IV. Downcomer velocity at top of tower.

TABLE 1

Summary of calculated results (I-VIII)

	Test I	Test II	Test III	Test IV	Test V	Test VI
I. Internal reflux at top of tower						
Lb. per hr.	41,700	28,350	19,650	13,160	7,710	10,580
Internal weight reflux to overhead product ratio at top of tower	6.96	5.75	3.71	3.53	2.32	2.55
II. Limiting vapor velocity at top of tower						
Free area, ft. per sec.	0.84	0.93	0.87	0.91	0.82	0.87
III. Actual vapor velocity at top of tower						
Free area, ft. per sec.	0.96	0.85	0.55	0.42	0.21	0.33
Slots, ft. per sec.	8.17	7.23	4.69	3.55	1.77	2.78
IV. Downcomer velocity at top of tower						
Top of downcomer, ft. per sec.	0.82	0.56	0.39	0.26	0.16	0.21
Under downcomer, ft. per sec.	1.02	0.70	0.48	0.32	0.20	0.27
V. Vaporization in reboiler						
Lb. per hr.	58,600	42,700	32,800	23,100	27,350	25,750
Reboiler weight vaporization to bottoms product ratio	3.92	2.81	1.53	1.36	0.69	0.99
VI. Limiting vapor velocity at bottom of tower						
Free area, ft. per sec.	0.79	0.83	0.83	0.88	0.78	0.83
VII. Actual vapor velocity at bottom of tower						
Free area, ft. per sec.	1.05	0.81	0.62	0.53	0.42	0.47
Slots, ft. per sec.	8.99	6.90	5.26	4.52	3.60	4.01
VIII. Downcomer velocity at bottom of tower						
Top of downcomer, ft. per sec.	1.34	1.05	0.99	0.73	1.17	0.90
Under downcomer, ft. per sec.	1.67	1.30	1.23	0.91	1.46	1.12

TABLE 2

Summary of tower performance—percent separation obtained (calculated result IX)

	Test I	Test II	Test III	Test IV	Test V	Test VI
Purpose of test—Cutting between	IC_5H_{12} and C_5H_{12}	IC_5H_{12} and C_5H_{12}	C_4H_{10} and IC_5H_{12}	C_4H_{10} and IC_5H_{12}	IC_5H_{12} and C_5H_{12}	IC_5H_{12} and C_5H_{12}
Feed rate, lb. per hr.	20,940	20,135	26,640	20,720	43,095	30,200
Overhead production rate, lb. per hr.	5,990	4,935	5,290	3,720	3,345	4,150
Bottoms production rate, lb. per hr.	14,950	15,200	21,350	17,000	39,750	26,050
External reflux rate, lb. per hr.	34,300	24,000	26,800	12,380	5,860	8,460
Percent butanes in feed removed overhead	100	100	100	90.8	67.2	95.8
Percent total pentanes in feed removed overhead	44.4	33.4	6.6	1.0	14.8	13.9
Percent isopentanes in feed removed overhead	76.8	65.0	Not separated		15.1	22.4
Percent normal pentanes in feed removed overhead	27.7	17.8	Not separated		14.6	13.9
Percent hexanes in feed removed overhead	0	0	0	0	0.1	0.03

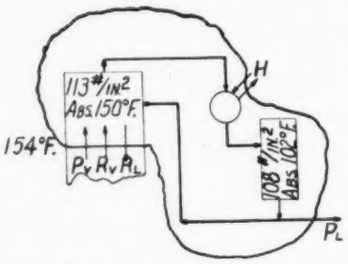


Fig. 5. Heat balance envelope around top tray

$$\frac{\text{Internal reflux}}{\text{Lb. per gal.}} = \frac{10{,}580 \text{ lb. per hr.}}{4.74}$$

= 2230 gal. per hr. at standard conditions.

Liquid cu. ft. per sec. at top tower conditions were calculated as follows:

$$\text{Liquid volume} = \frac{2230}{3600} \times \frac{0.569}{0.49} \times \frac{1}{7.48} = 0.095 \text{ cu. ft. per sec.}$$

$$\text{Velocity in top of downcomer} = \frac{0.095}{0.444} = 0.21 \text{ ft. per sec.}$$

$$\text{Velocity under downcomer} = \frac{0.095}{0.357} = 0.27 \text{ ft. per sec.}$$

These downcomer velocities are relatively low.

V. Vaporization in reboiler.

This quantity was calculated by equating the difference between total heat in and out of the tower in B.t.u. per hr. equal to total heat added in the reboiler. The difference between total heat added in the reboiler and sensible heat added in the reboiler in B.t.u. per hr. gave the heat added for vaporization. Dividing this by the total heat of the reboiler vapors in B.t.u. per lb. gave the pounds vaporized in the reboiler. These were determined as follows (temperatures are given in Table 10):

(Datum plane is 60°F. throughout)

(1) Total (sensible) heat entering in feed at 79°F., 30,200 (79-60) (0.513) (1.045) = 307,500 B.t.u. per hr.

(2) Total (sensible) heat leaving in bottoms through first exchanger 26,050 (293-207) (0.617) (1.022) = 1,543,000 B.t.u. per hr.

(3) Total (sensible) heat leaving in bottoms through second exchanger, 26,050 (207-147) (0.571) (1.022) = 913,000 B.t.u. per hr.

(4) Total (sensible) heat leaving in bottoms through cooler, 26,050 (147-85) (0.535) (1.022) = 884,000 B.t.u. per hr.

(5) Total (sensible) heat leaving in bottoms at 85°F., 26,050 (85-60) (0.509) (1.022) = 339,000 B.t.u. per hr.

(6) Sensible heat in unvaporized

TABLE 3

Heat exchanger performance (calculated result X) overhead condensers (two in series)

	Test I	Test II	Test III	Test IV	Test V	Test IV
Service:						
Shell side	Condensing overhead vapors					
Tube side	Water					
Effective external area, sq. ft.	926					
Log mean temp. difference (uncorrected)	54	50.5	52.7	42.0	30.5	37.5
Heat transferred, B.t.u. per hr. $\times 10^3$	6,260	4,560	3,275	2,300	1,480	1,912
Approach temp. (hot end) °F.	31.5	38	35	28	36	44.5
Approach temp. (cold end) °F.	86	66	76	61	25.5	31.3
U—B.t.u. per (hr.) (sq. ft.) (°F.)*	125.0	97.6	67.1	59.1	52.4	55.1
Shell side:						
Temp. in, °F.	173	150	147	129	161	147
Temp. out, °F.	133	115	119	104	96	102
Lb. per hr. vapor in	40,290	28,935	22,090	16,100	9,205	12,610
Lb. per hr. condensate	40,290	28,935	22,090	16,100	9,205	12,610
°A.P.I., vapor in	108	111	114	118	115	117
°A.P.I. condensate	108	111	114	118	115	117
Tube side:						
Temp. in, °F.	47	49	43	43	70.5	70.7
Temp. out, °F.	141.5	112	112	101	125	102.5
Gal. per mm. (calculated)	133	145	95	79	54	120
Lb. per hr. (calculated)	66,300	72,400	47,500	39,700	26,800	60,100

Tube data	No.	O.D., in.	Gauge	Length, in.	Material	Ext. surface, sq. in.
Upper condenser	298	$\frac{5}{8}$	18	120	{ Antimonial }	480
Lower condenser	278	$\frac{5}{8}$	18	120	{ Admiralty }	446

*Note: Good design transfer rate for this type unit when clean is U = 85 B.t.u. per (hr.) (sq. ft.) (°F.).

TABLE 4

Heat exchanger performance (calculated result X) reboiler

	Test I	Test II	Test III	Test IV	Test V	Test VI
Service:						
Shell side	Bottoms liquid and vapors					
Tube side	Steam					
Effective external area, sq. ft.	750					
Log mean temp. difference (uncorrected)	50.5	57	69	88.7	41	62.7
Heat transferred, B.t.u. per hr. $\times 10^3$	6,936	5,129	4,033	2,884	3,274	2,927
Approach temp. (hot end) °F.	43	51	62	82.5	36	59
Approach temp. (cold end) °F.	59	64	76	95	47	66
U—B.t.u. per (hr.) (sq. ft.) (°F.)*	183	120.2	78	43.5	106.5	62.3
Shell side:						
Temp. in, °F.	300	295	283	264	310	290
Temp. out, °F.	316	308	297	277	321	297
Lb. per hr. liquid in	73,550	57,900	54,150	40,100	67,100	51,800
Lb. per hr. vaporized	58,600	42,700	32,800	23,100	27,350	25,750
°A.P.I., liquid out	72.1	71	73.1	74.4	66.9	70.3
Mid-boiling point, °F., liquid out	162	164	158	154	194	171
°A.P.I., vapor out (assumed)	75	74	76	77	70	73
Tube side:						
Temp. in, °F.	359	359	359	359	357	356
Temp. out, °F.	359	359	359	359	357	356
Lb. per hr. (calculated)	8,030	5,930	4,660	3,340	3,790	3,390

Tube data:	No.	O.D., in.	Gauge	Length, in.	Material
	222	1	13	155	Steel

*Note: Good design transfer rate for this type unit when clean is U = 70 B.t.u. per (hr.) (sq. ft.) (°F.).

TABLE 5

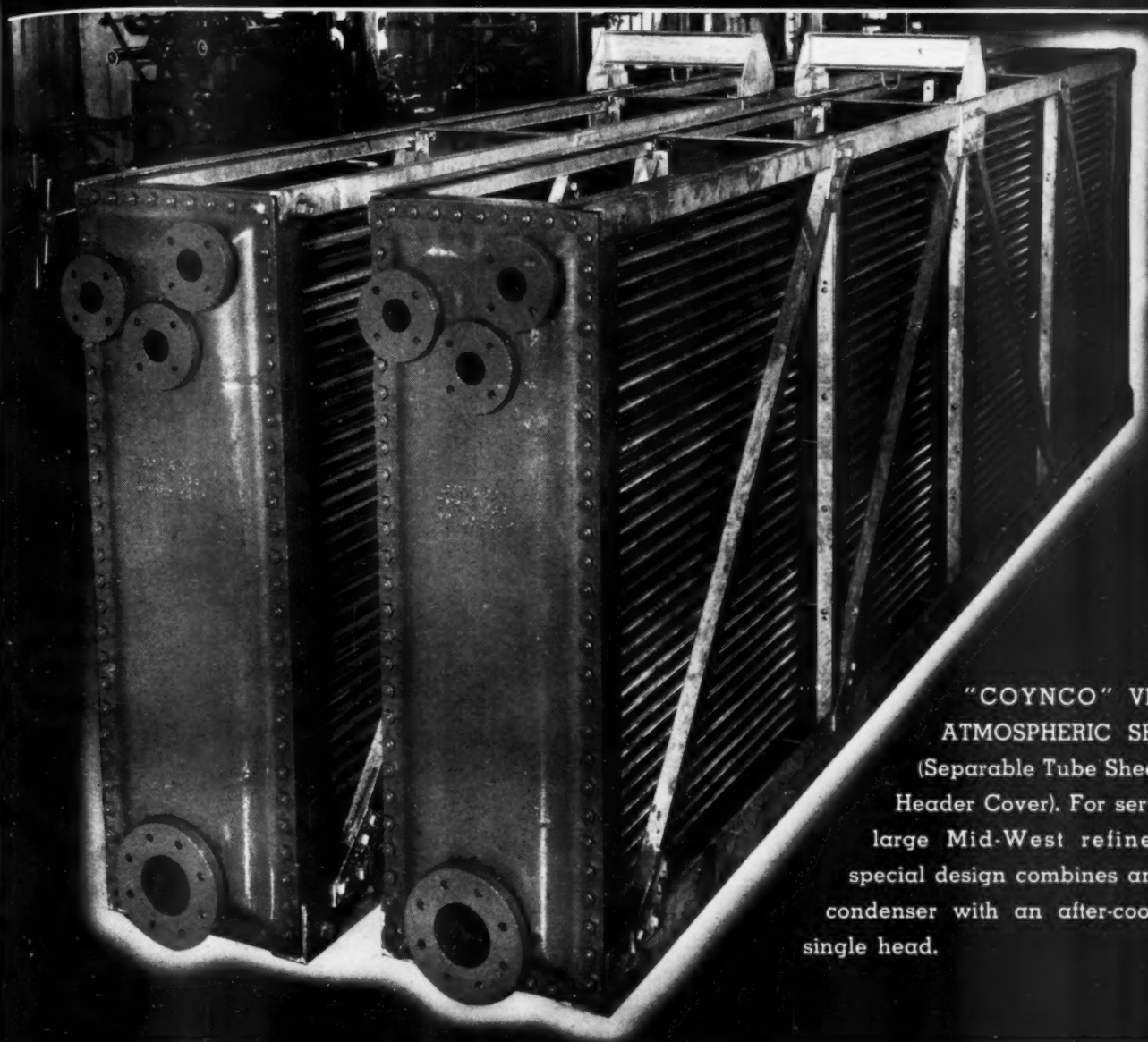
Heat exchanger performance (calculated result X) bottoms-feed exchanger No. 1

	Test I	Test II	Test III	Test IV	Test V	Test VI
Service:						
Shell size	Stabilized liquid bottoms					
Tube size	Raw feed liquid and vapors					
Effective external area, sq. ft.	567					
Log mean temp. difference (uncorrected)	59.5	59.0	53.5	46.0	66.5	61.0
Heat transferred, B.t.u. per hr. $\times 10^3$	1,178	1,203	1,295	920	2,045	1,543
Approach temp. (hot end) °F.	75	79	58	49	68	69
Approach temp. (cold end) °F.	46	43	49	43	65	53
U—B.t.u. per (hr.) (sq. ft.) (°F.)*	34.9	36.0	42.7	35.3	54.2	44.6
Shell side:						
Temp. in, °F.	308	302	287	266	315	293
Temp. out, °F.	183	175	191	179	234	207
Lb. per hr. liquid in	14,950	15,200	21,350	17,000	39,750	26,050
°A.P.I., liquid in	72.1	71.0	73.1	74.4	66.9	70.3
Mid-boiling point, °F., liquid in	162	164	158	154	194	171
Tube side:						
Temp. in, °F.	137	132	142	136	169	154
Temp. out, °F.	223	223	229	217	247	224
Lb. per hr. liquid in	20,940	20,135	26,640	20,720	43,095	30,200
°A.P.I., liquid in	82.2	81.1	81.1	81.8	70.7	76.4
Mid-boiling point, °F., liquid in	141	141	141	141	193	168

Tube data:	No.	O.D., in.	Gauge	Length, in.	Material
	270	$\frac{5}{8}$	18	155	Admiralty

*Note: Good design transfer rate for this type unit when clean is U = 60 B.t.u. per (hr.) (sq. ft.) (°F.).

"COYNCO"



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bottoms through reboiler, 26,050 (297-290) (0.641) (1.022) = 119,300 B.t.u. per hr.

(7) Total heat removed in condensers = 1,912,000 B.t.u. per hr.

(8) Total heat in overhead produced leaving reflux drum = 99,600 B.t.u. per hr.

Summarizing the above:

Heat entering tower B.t.u. per hr.	
(1)	307,500
(2) and (3)	2,456,000
Totals	2,763,500
Heat leaving tower B.t.u. per hr.	
(2) and (3)	2,456,000
(4)	884,000
(5)	339,000
(7)	1,912,000
(8)	99,600
	5,690,600
(—) Heat entering	2,763,500
Reboiler duty	2,927,100
(—) (6)	119,300
Heat for vaporization in reboiler	2,807,800

Pounds vaporized in reboiler = $\frac{2{,}807{,}800 \text{ (B.t.u. per hr.)}}{109 \text{ (B.t.u. per lb.)}}$ = 25,750 lb. per hr.

Reboiler weight vaporization to bottoms product ratio = $\frac{25{,}750}{26{,}050}$ = 0.99/1.

VI. Calculation of limiting vapor velocity in free area at bottom of tower.

Solving the critical velocity formula shown in (II) where:

$T = 297 + 460 = 757°F.$

$S = 0.582$ at 297°F.

$M = 87$

$P = 121$ lb. per sq. in. absolute

gave $V_c = 0.83$ ft. per sec.

VII. Calculation of actual vapor velocity at bottom of tower.

$$\text{Vapor volume} = \frac{\text{Lb. vaporized in reboiler}}{\text{Molecular weight}} = \frac{25{,}750}{87}$$

= 296 lb. moles per hr. at standard conditions

Correcting to conditions at bottom of tower (see Table 10), using method illustrated in (III) gave:

Pseudo critical pressure = 460 lb. per sq. in. absolute

$$\text{Reduced pressure} = \frac{121}{460} = 0.26$$

Pseudo critical temperature = 935°R

$$\text{Reduced temperature} = \frac{757}{935} = 0.81$$

Using reduced pressure and temperature as calculated above gave a compressibility factor of 0.765. The cor-

TABLE 6

Heat exchanger performance (calculated result X) bottoms-feed exchanger No. 2

	Test I	Test II	Test III	Test IV	Test V	Test VI
Service:						
Shell side	Stabilized liquid bottoms					
Tube side	Raw feed liquid and vapors					
Effective external area, sq. ft.	567					
Log mean temp. difference (uncorrected)	51	47.5	50.5	49	73	61
Heat transferred, B.t.u. per hr. × 10^3	522	487	885	561	1,530	913
Approach temp. (hot end) °F.	46	43	49	43	65	53
Approach temp. (cold end) °F.	56	52.5	52	56	82	68
U—B.t.u. per (hr.) (sq. ft.) (°F.)*	18.1	18.1	30.9	20.2	36.9	26.4
Shell side:						
Temp. in, °F.	183	175	191	179	234	207
Temp. out, °F.	122	118.5	119	122	169	147
Lb. per hr. liquid in	14,950	15,200	21,350	17,000	39,750	26,050
°A.P.I., liquid in	72.1	71	73.1	74.4	66.9	70.3
Mid-boiling point, °F., liquid in	162	164	158	154	194	171
Tube side:						
Temp. in, °F.	66	66	67	66	87	79
Temp. out, °F.	137	132	142	136	169	154
Lb. per hr. liquid in	20,940	20,135	26,640	20,720	43,095	30,200
°A.P.I., liquid in	82.2	81.1	81.1	81.8	70.7	76.4
Mid-boiling point, °F., liquid in	141	141	141	141	193	168

Tube data:	No.	O.D., in.	Gauge	Length, in.	Material
	270	5/8	18	155	Admiralty

*Note: Good design transfer rate for this type unit when clean is U = 60 B.t.u. per (hr.) (sq. ft.) (°F.).

TABLE 7

Heat exchanger performance (calculated result X) bottoms cooler

	Test I	Test II	Test III	Test VI	Test V	Test VI
Service:						
Shell side	Stabilized liquid bottoms					
Tube side	Water					
Effective external area, sq. ft.	567					
Log mean temp. difference (uncorrected)	35.5	33.7	42.5	41.0	51.2	29.5
Heat transferred, B.t.u. per hr. × 10^3	426	403	451	462	1,480	884
Approach temp. (hot end) °F.	55.5	52.5	49.0	56.5	76.5	53.0
Approach temp. (cold end) °F.	22	20	37	29	32	14.3
U—B.t.u. per (hr.) (sq. ft.) (°F.)*	21.1	21.1	18.7	19.9	50.6	52.8
Shell side:						
Temp. in, °F.	122	118.5	119	122	169.5	147
Temp. out, °F.	69	69	80	72	102.5	85
Lb. per hr. liquid in	14,950	15,200	21,350	17,000	39,750	26,050
°A.P.I., liquid in	72.1	71	73.1	74.4	66.9	70.3
Mid-boiling point, °F., liquid in	162	164	158	154	194	171
Tube side:						
Temp. in, °F.	47	49	43	43	70.5	70.7
Temp. out, °F.	66.5	66	70	65.5	93	94
Gal. per min. (calculated)	44	47	33	41	131	.76
Lb. per hr. (calculated)	21,850	23,700	16,700	20,500	65,700	37,900

Tube data:	No.	O.D., in.	Gauge	Length, in.	Material
	270	5/8	18	155	Admiralty

*Note: Good design transfer rate for this type unit when clean is U = 60 B.t.u. per (hr.) (sq. ft.) (°F.).

TABLE 8

Podbielniak analyses

	Test I	Test II	Test III	Test IV	Test V	Test VI
Condensed overhead product (see note)						
Hydrocarbon	Liq. percent*	Liq. percent†	Liq. percent	Liq. percent	Liq. percent	Liq. percent
Ethane	0.20	0.32	0.31	0.82	2.24	2.14
Propane	9.85	10.04	12.99	19.84	21.74	22.54
Isobutane	6.66	7.75	9.45	10.37	7.79	10.82
Normal butane	48.44	54.98	69.44	67.81	45.67	48.78
Isopentane	20.50	17.27	5.44	1.16	8.73	8.55
Normal pentane	14.35	9.64	2.37		12.62	6.81
Hexanes and heavier	....	....	....	....	1.21	0.36
	100.00	100.00	100.00	100.00	100.00	100.00
Stabilized bottoms						
Hydrocarbon	Liq. percent	Liq. percent	Liq. percent	Liq. percent	Liq. percent	Liq. percent
Isobutane	....	....	....	0.25	0.68	....
Normal butane	....	....	....	1.85	2.05	0.51
Isopentane	2.92	3.60	100.00	97.90	5.11	5.81
Normal pentane	17.57	17.20			7.71	12.93
Hexanes and heavier	79.51	79.20			84.45	80.75
	100.00	100.00	100.00	100.00	100.00	100.00
Grav., °A.P.I. of hexanes and heavier	66.0	65.8	73.1	73.1	62.2	65.3

*Distillation on residue from this sample when weathered gave a dry point of 96° F.
†Distillation on residue from this sample when weathered gave a dry point of 98° F.
Note: All percentages listed are actual liquid volume percent.

rected vapor volume then became:

$$\text{Vapor volume} = 296 \times 0.765 \times \frac{14.7}{121} \times \frac{757}{520} \times \frac{379}{3600}$$

$= 4.23$ cu. ft. per sec.

$$\text{Vapor velocity} = \frac{4.23}{9.0}$$

$= 0.47$ ft. per sec. in free area of tower at bottom.

$$\text{Vapor velocity} = \frac{4.23}{1.055}$$

$= 4.01$ ft. per sec. in slots on bottom plate.

The above figures show that the vapor velocities obtained at the bottom of the tower were also well below the critical for Test VI.

VIII. Downcomer velocity at bottom of tower.

$$\frac{\text{Reboiler vapors}}{\text{Lb. per gal.}} = \frac{25{,}750}{5.79}$$

$= 4460$ gal. per hr. at standard conditions

$$\frac{\text{Reboiler liquid}}{\text{Lb. per gal.}} = \frac{26{,}050}{5.84}$$

$= 4460$ gal. per hr. at standard conditions

Total downcomer liquid into reboiler $= 8{,}920$ gal. per hr.

Liquid cu. ft. per sec. at bottom tower conditions were calculated as follows:

$$\text{Liquid volume} = \frac{8{,}920}{3{,}600} \times \frac{0.698}{0.575} \times \frac{1}{7.48} = 0.40 \text{ cu. ft. per sec.}$$

$$\text{Velocity in top of downcomer} = \frac{0.40}{0.444} = 0.9 \text{ ft. per sec.}$$

$$\text{Velocity under downcomer} = \frac{0.44}{0.357} = 1.12 \text{ ft. per sec.}$$

Both of these downcomer velocities are above what is considered good design conditions, i.e., 0.8 ft. per sec.

Tabulation of Results and Data

This section summarizes the results and data obtained on all six tests in the following tables:

Table 1. Items I-VIII inclusive, illustrative calculations for which were given in the preceding section.

Table 2. Tower performance and percent separation obtained.

Tables 3-7. Heat exchanger performance.

Table 8. Podbielniak analyses on test samples.

Table 9. Laboratory inspection data on test samples.

Table 10. Crude naphtha stabilizer operating data.

Discussion

Unfortunately, the time available did not permit a more theoretical treatment by the calculation of plate efficiencies using plate-to-plate calculation methods. However, it is hoped that sufficient data has been offered to allow such calculations to be made in the future.

Because of the number of variables involved, it was felt that the results expressed in Tables 1, 2, and 8 would appear to better advantage in tabular form rather than graphical. A study of these two tables reveals that only in Test I was the limiting vapor velocity exceeded, and then only slightly in both top and bottom sections of the tower. This apparently did not impair the fractionation to any great extent, although in Test II, with lower vapor velocities, a better quality of overhead product was obtained, with relation to *iso*pentane concentration. However, a comparison of the results obtained in Tests I and II with those in V and VI, especially in regard to downcomer liquid velocities, is very interesting as shown below.

TABLE 9

Laboratory inspection data stabilized bottoms

	Test I	Test II	Test III	Test VI	Text V	Text VI
Reid vapor pressure, lb. per sq. in.	6.2	6.3	7.0	8.1	6.3	6.5
Gravity, °A.P.I.	71.1	71.0	73.1	74.4	66.9	70.3
I.B.P., °F.	120	122	114	102	110	108
10 percent	138	139	130	122	147	140
20 percent	144	145	137	132	159	148
30 percent	150	151	144	140	172	155
40 percent	156	157	151	146	183	164
50 percent	162	164	158	154	194	171
60 percent	172	173	168	164	204	181
70 percent	182	182	180	178	215	191
80 percent	196	196	193	192	230	205
90 percent	222	219	220	220	258	228
Endpoint, °F.	302	310	302	302	320	304
Present recovery	98	99	98	98	99	99
Percent residue	1	0.5	1	1	1	1
Percent loss	1	0.5	1	1	—	—

Laboratory inspection on data raw straight-run feed

	Tests I-IV	Test V	Test VI
Reid vapor pressure, lb. per sq. in.	23.0	15.8	21.0
Gravity, °A.P.I.	81.5	71.3	77.4
I.B.P., °F.	78	76	60
10 percent	96	123	106
20 percent	112	145	124
30 percent	124	164	141
40 percent	138	179	155
50 percent	152	193	168
60 percent	166	205	180
70 percent	182	219	195
80 percent	206	237	214
90 percent	...	287	292
Endpoint, °F.	292	318	294
Percent recovery	89	93	90.5
Percent residue	1	1	1.0
Percent loss	10	6	8.5

TABLE 10

Crude naphtha stabilizer test operating data

	Test I	Test II	Test III	Test IV	Test V	Test VI
Rates, bbl. per day (42 gal.)						
Raw feed	2175	2075	2750	2150	4230	3045
Stabilized bottoms	1480	1495	2120	1700	3830	2545
Overhead production	695	580	630	450	400	500
External reflux	3990	2810	2000	1500	700	1020
Pressures, lb. per sq. in. gauge						
Steam	136	136	136	136	132	131
Feed drum	17	18	15	16	25	30
Bottom of tower	120	109	109	94	117	106
Overhead into condensers*	...	...	...	...	113.5	98
Reflux drum	95	81	98	89	110	93
Temperatures, °F.						
Feed to No. 2 bottoms exchanger	66	66	67	66	87	79
Feed from No. 2 bottoms exchanger	137	132	142	136	169	154
Feed from No. 1 bottoms exchanger	233	223	229	217	247	224
Tower center	240	229	214	157	227	200
Bottoms to reboiler	300	295	285	268	310	290
Bottoms from reboiler	316	309	297	277	321	297
Bottom of tower	308	302	287	266	315	293
Bottoms out No. 1 bottoms exchanger	183	175	191	179	234	207
Bottoms out No. 2 bottoms exchanger	122	118.5	119	122	169	147
Bottoms out cooler	69	69	80	72	102.5	85
Water to cooler	47	49	43	43	70.5	70.7
Water from cooler	66.5	66	70	65.5	93	94
Top tower	178	158	151	132	163	150
Overhead into top condenser	173	150	147	129	161	147
Overhead out top condenser	162	138	141	124	132	122
Overhead out lower condenser	133	115	119	104	96	102
Water to lower condenser	47	49	43	43	70.5	70.7
Water from lower condenser	88	71.5	67.5	60.5	87	81.5
Water from top condenser	141.5	112	112	101	125	102.5

*(No connection for first 4 tests.)

High downcomer velocities in Tests I and II were brought about by the use of large quantities of outside reflux causing high internal reflux ratios in both the top and bottom sections. Here again lower velocities apparently favored the fractionation in Test II over I. In Tests V and VI, high downcomer velocities were brought about by the use of high feed rates, with a resultant definite limitation in the quantity of external reflux possible to pump back to the tower. This in turn resulted in low internal reflux ratios in both the top and bottom sections of the tower, with a marked decrease in fractionating efficiency. This was evidenced by the quantities of butane left in the bottoms, while hexanes were present in the overhead. Test V with a much higher feed rate than Test VI gave much poorer results, while both these tests suffer by comparison with I and II, neither of which had any butanes in the bottoms or hexanes in the overhead.

Tests III and IV, in which a cut was attempted in the overhead product between normal butane and *iso*pentane, gave good results. Each test was well below the limiting vapor velocities in both top and bottom sections. However, Test III, with higher downcomer velocities than IV, showed a poorer overhead cut, containing considerably more pentanes. In both these tests, high downcomer velocities were maintained by the use of quantities of external reflux, with resultant high ratios of internal reflux in the top and bottom sections of the tower.

Tables 3 through 7 present data and results on the heat exchanger performance obtained during the six tests. In nearly every case, the overall external heat transfer coefficients vary directly with the velocity or quantity of the materials passing through them.

Table 9 presents laboratory inspection data results, indicating the degree of front end separation of each of the stabilized bottoms products.

Table 10 presents average test data as obtained in the field and as used in all the calculations reported in this paper.

Post-War Rubber Use May Be Doubled

World consumption of natural and synthetic rubber after the war may reach a total of 2,000,000 tons a year, nearly twice as much as ever consumed even in the biggest years up to now, John L. Collyer, president of The B. F. Goodrich Company, stated recently.

In a talk before the New York State Chamber of Commerce on "the basis for a post-emergency policy in rubber," Collyer said he based this prediction on the assumption that sound policies would be followed and "low-cost rubber—natural or man-made, probably both—would be available throughout the post-war world."

Collyer said it is "no longer a foregone conclusion" that the Japanese will destroy the Far East rubber plantations when they are driven out, as "we shall soon be able to rely upon synthetic rubber production, and therefore destruction of the trees would not have the effect now, as it once would have had, of seriously crippling the United Nations' ability to fight and win the war."

The speaker recommended that the nation's synthetic rubber facilities be kept intact and in operation "on at least a limited basis, say 150,000 to 200,000 or more tons production a year," after the war. He said "it seems inevitable that the American people will want to continue at least standby operation of these plants—just as they will want to retain air bases and battleships."

Collyer said he felt that those responsible for the nation's defense would want to continue to specify synthetic rubber's use in national defense equipment in sufficient amounts to assure continuing operation of the large-scale plants. This, he pointed out, would "assure us of adequate production capacity for use in any emergency, and reasonable protection against high prices of natural rubber."

As for the near-term likelihood of general-purpose synthetic rubber's being able to compete with natural rubber in price, Collyer said that estimates of the all-around economic potentialities of synthetic rubber are being favorably revised all the time in the light of technical advances. He indicated that progress has "run well ahead of expectations, both as to indicated capacities of given plants and in the adaptation of the material to necessary uses."

A clue to the progress being made, as reflected in price, he said, was seen in the fact that whereas his estimate three years ago before a Senate committee that synthetic rubber could be produced on a large scale in this country for as low as 25 cents a pound was received with general skepticism, the office of Rubber Director Jeffers recently has been reported as mentioning the likelihood of synthetic rubber at 16 cents a pound.

Conclusions

It is believed that the following points have been brought out and can be considered to hold generally for bell-cap fractionating towers with 18-in. tray spacing and of the general design reported:

1. For identical quantities of reboiler liquid entering a reboiler:

(A) Fractionation suffers from flooding and downcomer liquid velocities in lower portion of tower become excessive at following rates:

(1) 1.5 ft. per sec. when reboiler weight vaporization to bottoms ratio is held above 3 to 1.

(2) 1 ft. per sec. when reboiler weight vaporization to bottoms ratio is held above 1.5 to 1.

(B) Fractionation is satisfactory when downcomer liquid velocities in lower portion of tower are maintained below following rate:

(1) 0.9 ft. per sec. when reboiler weight vaporization to bottoms ratio is maintained at a minimum of 1.4 to 1.

2. Fractionation suffers somewhat when actual vapor velocities in either top or bottom sections of the tower exceed the critical velocities as calculated by the formula:

$$V_c = 4.04\sqrt{\frac{TS}{MP}}$$

Acknowledgment

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Tepetate—Six Years Later*

By

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THE first discussion of Continental Oil Company's Tepetate, Louisiana, high-pressure, field stabilization, gasoline and pressure-maintenance plant operation was given before the Natural Gasoline Association of America at its annual meeting in May, 1937. As this operation was the first of its kind in the petroleum and natural gasoline industry, it is believed that a review of its performance during the last six years will be of interest to those contemplating such operations and to the industry generally.

The Tepetate field is unique among oil fields, as all phases of operation are concentrated at a central location in the pool. Oil and gas production from high-pressure wells is carried through single lines to high-pressure separators for each lease, which are located in a battery in the central plant. Gas from the separators is metered and passed through high-pressure absorbers for the removal of the condensible liquid hydrocarbons. Gas from the absorbers is compressed and returned to the producing formation. Natural gasoline recovered from the gas, along with propane, *iso*butane, and normal butane, is delivered by pipe line to the company's refinery at Lake Charles, where it is used in the manufacture of aviation alkylate, a product used in making 100-octane aviation gasoline.

Oil from the primary separators is metered and commingled in a common stream after which it passes through a crude oil stabilizer. In the stabilizer the crude is denuded of the light fractions that normally would be lost in storage. The light fractions from the stabilizer are recovered as liquids in the natural gasoline recovery section of the plant. Oil from the plant stabilizer is run to the pipe-line station in the central plant and is pumped to the company's Lake Charles Refinery where part of it is processed. The remainder is shipped either by rail or by tanker from the loading terminal adjacent to the Lake Charles terminal and refinery.

The centralization of the field operations has eliminated a low-pressure field gathering system and lease tanks and has greatly reduced the labor required for conducting all field operations.

*Presented before Natural Gasoline Association of America, Dallas, Texas, April 14-16, 1943.

Pressure Maintenance

The Tepetate field has been producing for more than seven years, and pressure-maintenance operations have been conducted for more than six years of this time. The oil recovery to date is greater than the estimated ultimate recovery would have been had the field been produced in the conventional manner. The estimated recovery from this pool by ordinary means of production was 11,000,000 bbl. Production to date is nearly 12,000,000 bbl. All oil subsequently recovered to the economic depletion of the pool will be obtained on account of the continuous return of gas to the producing formation. The ultimate recovery, under the plan instituted, is expected to be as much as 150 to 175 percent of the ultimate that would have been produced by normal recovery methods. The pool is currently producing at the rate of 2750 bbl. per day. This rate is determined by and limited to the number of barrels it can produce consistent with good production practice rather than an amount required for market demand. Producing rates should always be governed in this manner except where production demands of strategic crude on account of war emergency may exist.

Effect of Gas Returned

During the last six years more than 32,000,000,000 cu. ft. of gas have been compressed and returned to the producing formation. Under existing subsurface temperature and pressure conditions, this gas occupies reservoir pore space equivalent to that of 43,500,000 bbl. of liquid, and its return to the producing formation has been responsible in greatly retarding the rate of pressure decline and water encroachment.

The line on Fig. 1 shows the relationship between cumulative production and pressure decline. The effect of the gas returned is reflected in the change of slope of the pressure decline line. If the above volume of gas had not been returned, it is estimated that the present formation pressure of 2345 lb. per sq. in. would have been reduced to 1400 lb. per sq. in., as shown by the extension of the pressure decline curve slope established before any gas was returned; thus a saving of 945 lb. per sq. in. of formation pressure has been made. The energy stored in the reservoir by this gas conservation program is sufficient to flow all the recoverable oil the pool will ever produce. The saving of pumping equipment otherwise required and the reduced lifting cost for the oil produced up to the present time have been more than sufficient to pay for the entire installation of all necessary equipment for compressing and returning gas to the producing formation.

The 32,000,000,000 cu. ft. of gas returned to the producing formation at Tepetate contains 41,600,000,000,000 B.t.u. of heat energy, which is equivalent to the heat energy in 1,500,000 tons of average dry bituminous coal.

From a fuel angle, gas saved in a closed reservoir is considered the same as known deposits of coal in a mine. Gas for fuel, however, may be produced with less effort and expense than a heat value equivalent from a coal mine and in a much shorter time.

Effect on Gasoline Content

Fig. 2 shows a cross-sectional view of the Tepetate field under original reservoir conditions. It will be noted that the gas-oil contact plane is 8254 and the water-oil contact is 8282 ft. Both measurements are subsea levels and were obtained from a careful analysis of electric logs taken in each well as it was drilled. These data show the original sand section saturated with oil to be approximately 28 ft. thick.

Fig. 3 shows the relative positions of the gas-oil and water-oil contact planes after seven years of continuous operation. The original gas-oil contact plane has been lowered 3 ft. and the water-oil plane raised 14 ft., leaving approximately 11 ft. of saturated section. It was planned to have the gas-contact and water-contact planes approach the center of the section at the same rate, but the sale of some gas prevented the gas cap expansion originally anticipated.

Wells were originally completed in the approximate center of the 28-ft. saturated section with only 30 in. of perforations in the casing. As the rising water table approached the bottom of these perforations and the wells began to produce water, they were plugged-back and reperforated slightly higher. The plugging-back and reperforating in only a few feet of sand 8300 ft. below the surface is a very difficult job;

however, good results have been accomplished. To date the water encroachment has necessitated the reworking of 33 wells and the abandonment of 4 edge wells.

With the lowering gas-oil contact plane, as shown by Fig. 3, it can be seen that, as the field becomes older, gas-oil ratios will continue to increase because of gas coning at producing wells on account of differential pressure and an ever-thinning liquid seal over the casing perforations. Production rates must be controlled at all times to maintain a liquid seal over the casing perforations. The shorter the length of casing perforations the more readily such control may be effected. The last six years' performance of this pool has proved the advisability of completing wells as described.

It would first appear that an increase in gas-oil ratio would decrease the percentage of recoverable liquid hydrocarbons from the produced gas. This, however, has not happened, and a comparison of analyses for liquid hydrocarbon recovery made at the beginning of operations and at this time shows that there has been practically no change. The first analysis was made in 1936, the last one this year.

Fig. 4 shows a cross-sectional view of the Tepetate field. It also shows the amount of gas returned in the densely shaded section and the present location of such gas. The gas in the structure above the oil level was in equilibrium with the oil in the saturated section prior to any development; and since the dry residue gas was returned to the crest of the structure, there has been no by-passing of dry gas into wells producing oil. The gas produced with the oil is either solution gas or free gas in equilibrium with the oil from the gas cap adjacent to the wells. Its quality remains practically constant and will continue to do so until enough gas has been produced with the oil and sufficient dry gas returned to displace the entire original volume of gas in the gas cap. Experience indicates that dry gas returned to the top of the structure does not readily mix with the wet gas in the cap but displaces the wet gas ahead of it as additional volumes are injected. Due to the existence of the above action, it can be seen that the performance of the gasoline plant will remain practically constant over a period of many more years. It is further indicated that when the gas cap becomes completely filled with dry residue gas, such residue may be forced into and through the oil zone before being produced and that it will become partially saturated with condensible hydrocarbons and further extend the operating plant life and add to the total liquid hydrocarbon recovery. A gasoline plant operating in connection with this type of field practice is more assured of a financial pay-out without many of the hazards normally encountered. When this process has reached its economic limit, the volume of gas saved up to that time will be available for market use, for reforming to synthetics, or for use as fuel.

Gas returned since the beginning of gasoline recovery operations has maintained the pressure high enough to assure continued uniform operation of the high-pressure absorber plant and present indications are that this plant may be kept operating by well pressure to the economic limitations of oil and liquid hydrocarbon recovery. This fact is emphasized as there has been considerable discussion concerning the advisability of high-pressure operations on account of possible plant obsolescence due to well pressure depletion before proper recovery was made. It can now be definitely stated that, in connection with pressure-maintenance systems properly operated, high-pressure absorption processes are cheapest and most economical and may be operated with no more difficulty than any of the generally known low-pressure processes. Since the Tepetate plant was placed in operation, many absorption plants operating at much higher pressures have proved the efficiency and wisdom of development in this direction. Plants with operating pressure approaching 2000 lb. per sq. in. are now giving excellent recoveries in absorbing light hydrocarbons that were formerly inefficiently recovered by retrograde condensation. It now appears that, by recirculating the heavy molecular cut out of a liquid recovered from gas by retrograde condensation as an absorbent media, operation pressures far in excess of 2000 lb. per sq. in. may be used; and certain recovery operations heretofore considered impractical will become commercially attractive.

One of the numerous benefits of a gasoline plant operation in connection with a properly controlled field stabilization and pressure-maintenance system is the uniform rate of production that may be maintained. In the Tepetate field the plant throughput has been very constant day after day, and load peaks have been eliminated. Any plant operator will appreciate the value of such a condition existing over a period of years, both from an operating and a producing angle. Although this plant and pool are owned by one operator, the same type of operation is being obtained by coöperative arrangements in areas of divided ownership.

Liquid Meters

In order to operate a field stabilization plant in connection with natural gasoline recovery operations, it is necessary that all liquids produced from the wells be measured under pressure until such well liquids have been stabilized to pipe-line conditions.

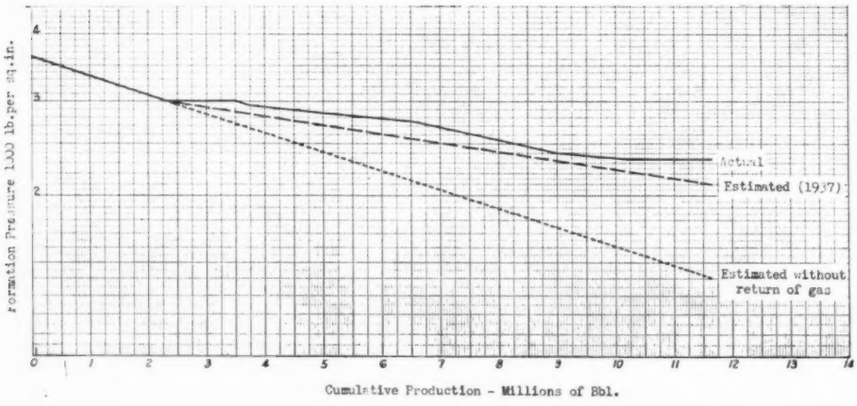
The only practical manner that this operation has developed by which liquids can be accurately measured under pressure is with meters. Such meters are either of the rotating or reciprocating piston type.

Many millions of barrels of oil have been measured by meters in the Tepetate field, and no particular difficulties have been encountered. Normal wear and tear on meters due to amorphous sediment in crude oil must be expected, and periodic inspection and adjustments must be made to keep meters in proper working order. Experience has shown that filters having suitable permeabilities for the stopping of sediments that cause wear will become plugged after very short operating periods and that their use cannot be justified.

High-Pressure Meters

Meters for use in measuring high-pressure liquids are expensive because

Fig. 1. Cumulative production—pressure decline, Tepetate, Louisiana



of the design and materials required to withstand the differential between the line pressure and atmosphere. Fig. 5 shows an arrangement in general use at Tepetate whereby a 25- or 50-lb. working pressure meter may be used for operation on any pressure up to several thousand pounds per square inch. The method consists of installing the meter in a secondary case with its intake connection open to the inside of the case. The discharge connection of the meter is carried out of the secondary case through a suitable stuffingbox as shown. Pressures of any magnitude may be packed off in such a stuffingbox. As shown in the sketch for the meter setting, the outer casing may be made with a settling trap at the bottom for the accumulation of sand and other large particles. This settling trap has been found advantageous in eliminating wear and tear on the meters. The counter driveshaft is taken through the outer shell through a small Timken bearing and stuffingbox and has operated in a satisfactory manner. Magnetic drives through a nonmagnetic diaphragm are now being developed and will eliminate the necessity of the stuffingbox and bearing. Where many positive displacement meters are used in a battery, it has been found advisable to install an overhead craneway to aid in removing any particular meter for inspection, calibration, and repair. At Tepetate the craneway extends over the meters and into the meter repair shop at the end of the installation row.

Outside Equipment

Six years of operating experience has definitely indicated that outside installation of motor-driven pumps and boilers is feasible and practicable and minimizes initial plant installation and depreciation costs by the elimination of buildings. This type of installation, however, is not recommended for regions where temperatures far below freezing exist during winter months.

Header and Piping

Elevated engine room floors with all high-pressure lines brought outside under such floor levels but above outside grade lines with all headers exposed have proved advantageous from a maintenance and inspection standpoint. This general arrangement has been almost universally adopted by the industry in the design of plants in connection with high-pressure gasoline and condensate recovery plant operations.

High-Pressure Lines

The only failures of welded connections that have been observed have been a few hairline cracks immediately adjacent to welds in lines tying into compressor cylinders. It is believed that these have been due to the use of too heavy beads in the initial welding and that a multiplicity of lighter beads on thick walled pipe will eliminate such occurrences. In no case has any leak of consequence developed, and those appearing have been satisfactorily repaired by welding.

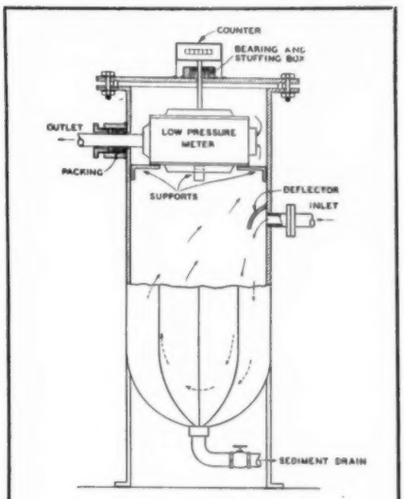


Fig. 5

Alloy grade drill pipe was used for certain high-pressure field lines when suitable medium carbon steel was not available. Difficulty was experienced in welding such lines, as such pipe was originally designed for screwed connections; and no suitable welding rod material was available. As there is a shortage of critical materials due to the war, operators may be forced to the use of alloy grade pipe on hand; and they should take extreme precautions when fabricating such pipe by welding.

Check Valves

The initially designed nonreturn valves for high-pressure gas lines at Tepetate were equipped with ball and cage checks, as no suitable check valves were available at the time of plant installation. Pulsations caused by compressor surges of dense gas caused the balls to oscillate and pound against their cages and seats, causing undue wear. Wafer type valves similar to those used in compressors have been substituted and this trouble eliminated. The use of wafer-type, nonreturn valves is recommended for all high-pressure gas lines receiving their supply from compressor cylinders.

Desalting of Crude

One of the first large desalting plants was installed at Tepetate for the removal of salt from the hydrocarbon liquids produced. Wellhead liquids carry salt content as high as 2465 g. per bbl. This liquid is treated with an average of 0.00183 gal. of chemical per bbl. and then run through electrostatic precipitators where the salt content is reduced to approximately 1.3 g. per bbl. Several years'

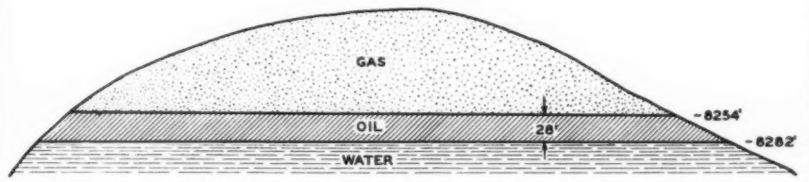


Fig. 2

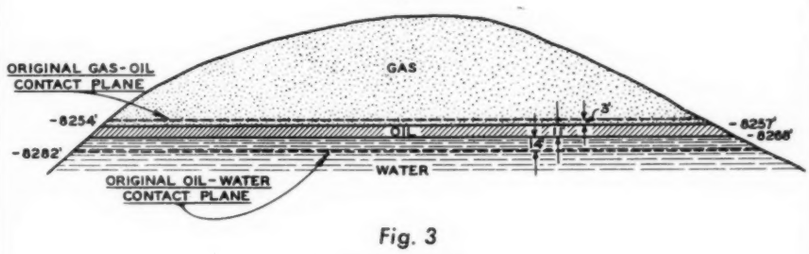


Fig. 3

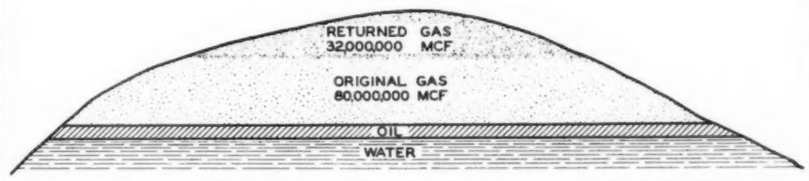


Fig. 4

operation of this type of desalting equipment has definitely proved its worth in plant operation and has eliminated many thousands of dollars of wear and tear on refinery heat exchange equipment. During the operation of desalting, dehydration is also accomplished, and no further treatment of the well production for water removal is required.

Blow-Out Safety Discs

Frangible type rupture disks in lieu of safety valves have proved efficient and satisfactory. Experience has indicated that the discharge lines below safety disks should never be manifolded together to a vent, as the pressure surge on the downstream side of the disks will cause them all to rupture when any one disk fails.

Header Hold-Down Clamps

The header hold-down clamps used in this plant consist of a U-shaped stirrup over the header. The ends of the stirrup are welded onto a plate set in the concrete supporting block. Three set screws pass through the stirrup in radial alignment toward the center of the header pipe. These set screws are backed away from the header until operating temperatures are reached and are then tightened down just enough to stop vibration. A sole plate is used at the end of the set screw to prevent it from abrading the pipe. This arrangement permits motion due to temperature change and has been entirely satisfactory. Its use has been generally adopted in most high-pressure operations.

Plant Ventilation

Forced-draft ventilation in engine and compressor rooms has proved advantageous, and its use is recommended for all high-pressure plant operations.

Motor-driven uptake fans placed at the ridge of the plant building have been found to give best results. With such units, engine and compressor rooms have been kept to workable temperatures and explosion hazards minimized. Complete explosion-proof electrical equipment should always be used.

Conclusion

In concluding we note the closing paragraph of an article on stabilization by F. L. Kallam*:

"It is the writer's concluding opinion that crude-oil stabilization can be adapted to many of our domestic fields in sizes commensurate with the local conditions. Fundamentally, no issue can be taken with a process which cures evaporation loss at the source and makes unnecessary the subsequent recovery of such losses in order to prevent economic waste. In all new fields, and in many of the existing fields, the system of crude-oil stabilization should be carefully considered in view of its possibilities for greater efficiency and economy in conserving our petroleum resources."

It should be emphasized that the successful operation of an integrated plant such as the one at Tepetate, which involves three operating divisions of the company; namely, the production, natural gasoline and gas, and pipe-line divisions, requires the full coöperation of each and close coördination between all. This has been accomplished with gratifying results under the direct supervision of the natural gasoline and gas division.

In acknowledgment for many of the innovations that made the construction and operation of such an integrated plant feasible credit must be given to the field men of all divisions.

*"Stabilization of Crude Oil," by F. L. Kallam, *Petroleum Refiner*, March, 1943.

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A-42	B-60	C-81	D-162
A-46	B-68	C-85	D-173
A-51	B-75	C-90	D-180
A-60	B-81	C-96	D-195
A-68	B-85	C-105	D-210
A-75	B-90	C-112	D-240
A-80	B-97	C-120	D-270
A-85	B-105	C-128	D-300
A-90	B-112	C-144	D-330
A-96	B-120	C-158	D-360
A-105	B-128	C-162	E WIDTH
A-112	B-144	C-173	E-180
A-120	B-158	C-180	E-195
A-128	B-173	C-195	E-210
	B-180	C-210	E-240
	B-195	C-240	E-270
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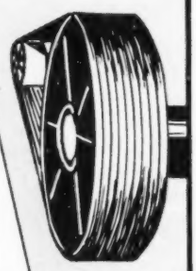

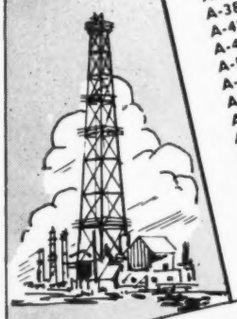

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Trends in Centrifugal Refinery Pumps*

By K. P. HURLEY and DREW T. WHITING
Ingersoll-Rand Company

THE manufacturer who proposes to keep his products fitted to the changes in refinery requirements should have an active field organization, a flexible design staff, and a crystal ball. It is interesting to review the changes during the last 12 years, starting off with severely depressed business conditions and proceeding through changes of all kinds up to the unprecedented wave of construction during the last two years.

The most severe problem 12 years ago was to recycle hot oil through cracking coils. A great amount of money and research were required to produce reliable pumps for this duty. Good results were obtained by several manufacturers, and by the middle '30's reliable pump operation was considered a commonplace. Perfection of details followed and fine pumps were produced. At the peak of this pump development refineries began to change to great chemical plants, and the market for high-pressure hot oil pumps began to disappear. (Fig. 1). It seemed that they would have no place in the refinery of the future. This did not turn out to be true, as services requiring such pumps did develop as will be mentioned later. (Fig. 2).

New terms began to appear — catalytic cracking, thermal alkylation, sulphuric acid alkylation, isomerization, polyform, powdered catalyst, thermofor, hydroformer, hydrofluoric acid alkylation, toluene, butadiene, styrene, co-polymerization, and many others straight from the chemistry book. The authors make no pretense of understanding all these manifestations of organic chemistry in action, but have had some experiences with the pumps required.

Certain catalytic cracking plants brought with them new problems, some of them so novel as to require pumps of totally new design unlike anything ever seen in a refinery. The circulation of molten salts in large quantities (6,000 to 17,500 gal. per min.) against low heads (40 to 75 ft.) with temperatures of 850°F. could not be handled by conventional pumps. A vertical pump of axial or mixed flow was a perfect solution, and structural problems were soon solved. Fortunately, no new metallurgical problems had to be considered, and these pumps are now more or less standard products. (Fig. 3).

The other pumps required are of conventional refinery design, but one innovation in refinery practice is the use of large centrifugal blowers driven by hot gas turbines or steam turbines. These are high horsepower machines running at speeds that make the high-speed pump (3600 r.p.m.) seem to stand still. The first of these blowers were built in Switzerland, but are now made in this country. (Fig. 4). In some plants, reciprocating compressors perform the same function.

Some of the first alkylation plants employed hot sulphuric acid and this presented severe problems, mainly concerned with packing. Pumps were designed to reduce pressure on the packing to the minimum possible, and deep boxes were needed. (Fig. 5). Spun glass packing lubricated by injected butane worked out well. In recent plants, the acid-hydrocarbon mixture is pumped cold. Special pumps with very deep boxes were still needed and a new problem appeared. At the beginning of the cycle, the pure acid had to be pumped, with more and more thinning out by addition of hydrocarbons and increased temperature as the run progressed. This meant a change from high to low viscosity, and required great care in sizing drivers, to prevent overloads during the first part of the operation. Because of the great changes in load, steam turbine drivers were favored as variable speed was desirable. No particular metallurgical problems appeared; all iron pumps offer excellent resistance to the action of the acid. Safety regulations in many plants, however, required steel pump casings for acid hydrocarbon mixtures having vapor pressures higher than atmospheric. This precaution was to provide greater safety in case of fire; water sprayed upon a hot cast-iron casing might cause it to crack open, diffusing its contents over a wide area in gaseous form. In similar circumstances the steel casing would become plastic and deform but would not break open. Steel does not resist the acid as well as cast iron, but safety is more important than longer wear.

Anhydrous hydrofluoric acid is used in certain new alkylation plants, and one of the most vital requirements of proper pump design is that the acid be prevented from coming in contact with the packing. (Figs. 6 and 7). Various designs of stuffingboxes have been proposed, all of them relying upon injection of alkylate bottoms or similar material ahead of the packing and at higher pressure than that existing at the entrance to the stuffingbox. The maintenance of this pressure differential is too

*Presented before Western Petroleum Refiners Association, Shreveport, Louisiana, August 14, 1942.

Fig. 1

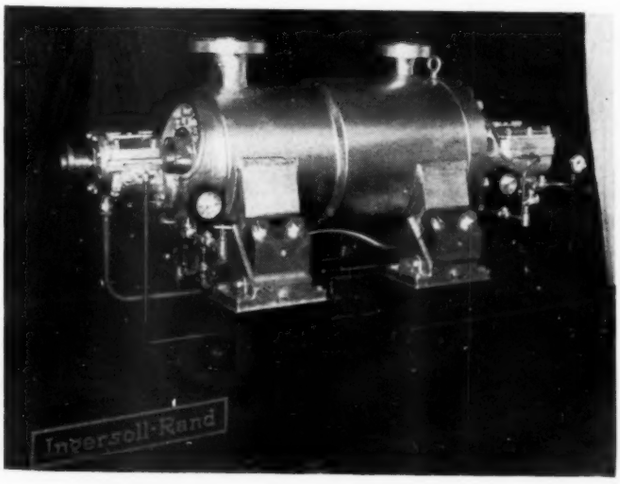
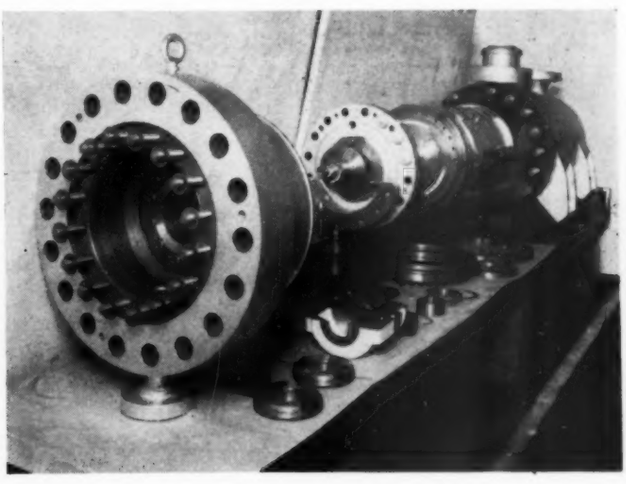


Fig. 2



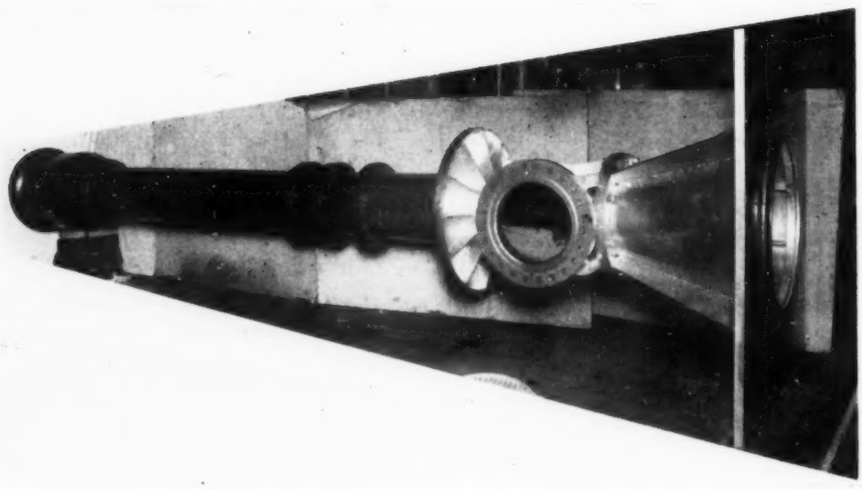


Fig. 3

important to depend upon hand adjustment. A control system should be provided so that the injected material will always flow into the pump. It is also a good idea to inject a lubricant into the packing as the sealing liquid is quite dry. Mechanical sealing devices, using no packing, have been suggested and will probably be tried, but the process is relatively new and it will be some time before complete data are obtained.

Cast iron also stands up well under the action of anhydrous HF, or HF-hydrocarbon mixtures, and carbon steel casings apparently have reasonable resistance.

In order to reduce rubbing speed against the packing, it is proposed to eliminate the conventional shaft sleeve. The bare shaft may be run through the packing area, but it requires flame hardening to produce a hard surface. An alternative is to reduce the shaft diameter and shrink on a hardened sleeve having the same O. D. as the shaft. After shrinking on, the shaft is placed between centers and the sleeve is ground to perfect concentricity and high finish.

In some plants isomerization of normal butanes to obtain *iso*butane is necessary in order to maintain the feed to the alkylation plant. Most of the pump duties require only one or two stage refinery pumps already available, but in some cases hydrochloric acid must be pumped. So far, this has been done with special reciprocating pumps. It may well be that suitable centrifugal pumps will be made available but nothing definite appears now.

In the manufacture of toluene, the pump duties are similar to those normally encountered in fractional distillation, but are larger and more numerous due to the high capacities handled and the great number of towers required to procure close fractionation. The bottoms pumps may handle 1800 to 2000 gal. per min. against heads high enough to require 3450 r.p.m., and the pumps must be designed for hot oil service. Such a pump is shown in Fig. 8. The impeller is double suction and the pump discharge passage is of double volute design to neutralize radial thrust. The suction passages are generous in order to permit operation with low submergence.

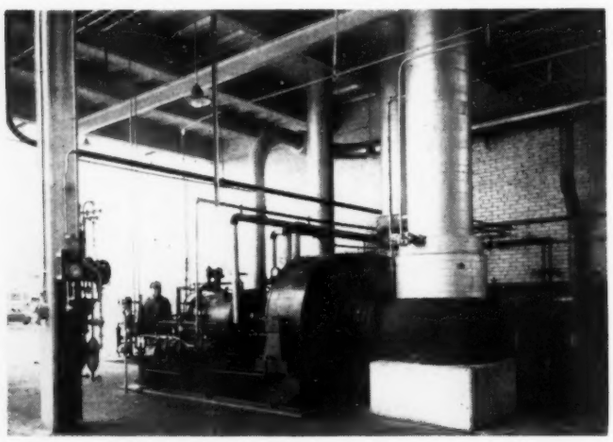


Fig. 4

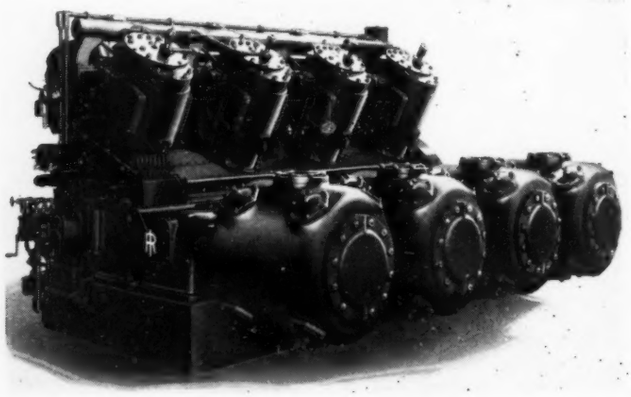


Fig. 5

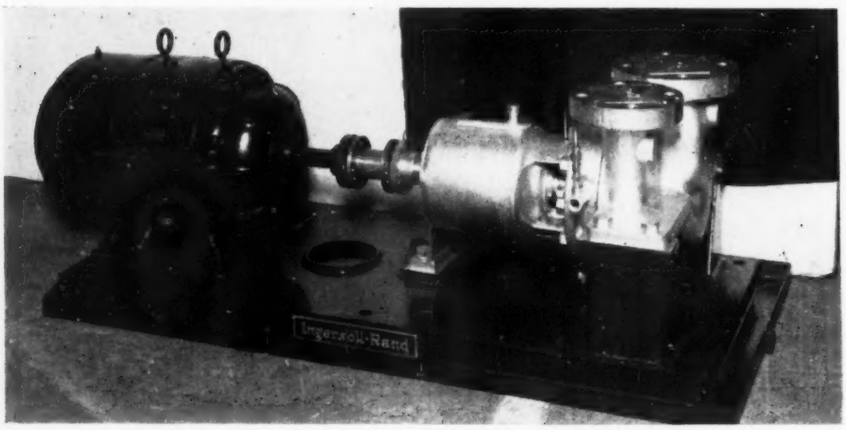


Fig. 6

In some toluene plants, phenol must be pumped, and this requires careful study of the stuffingbox design and the materials for certain parts. Care must be taken to confine any leakage from the packing. The capacity and head conditions are within the range of single stage, overhung impeller pumps, having only one stuffingbox. (Fig. 9). A glass window enclosure over each opening to the packing gland is simple and effective. Any leakage is carried off through a pipe connected to the housing below the packing gland. This pipe is traced

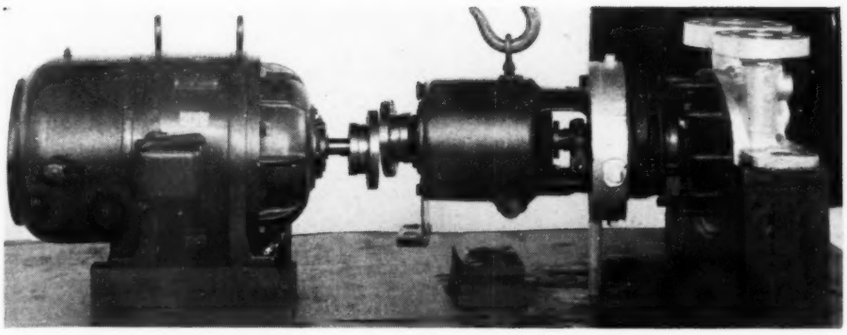


Fig. 7

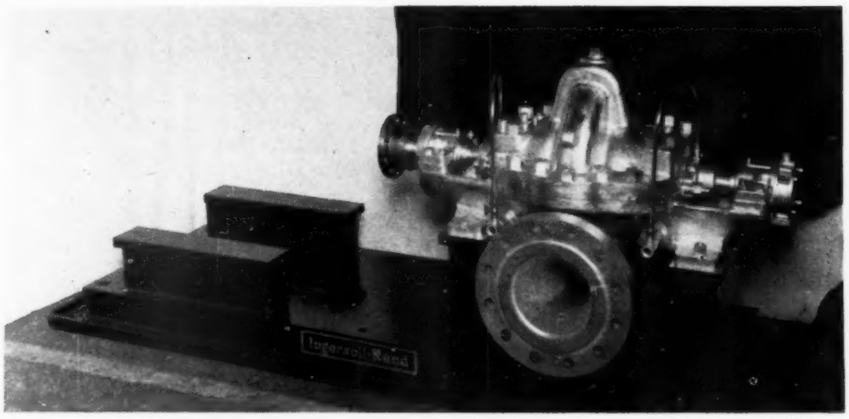


Fig. 8

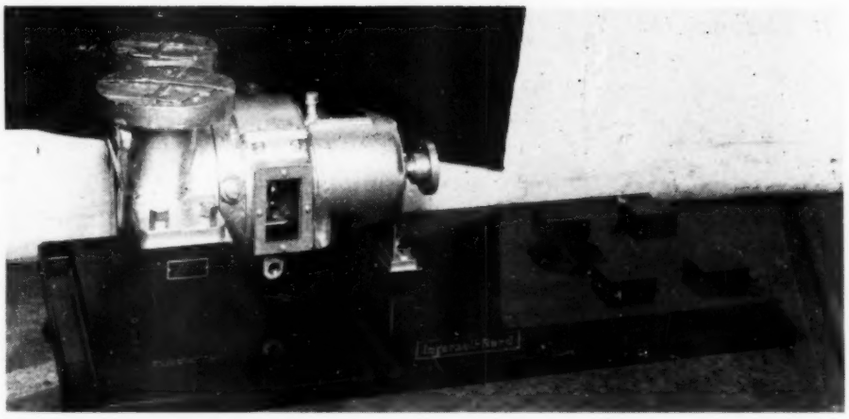


Fig. 9

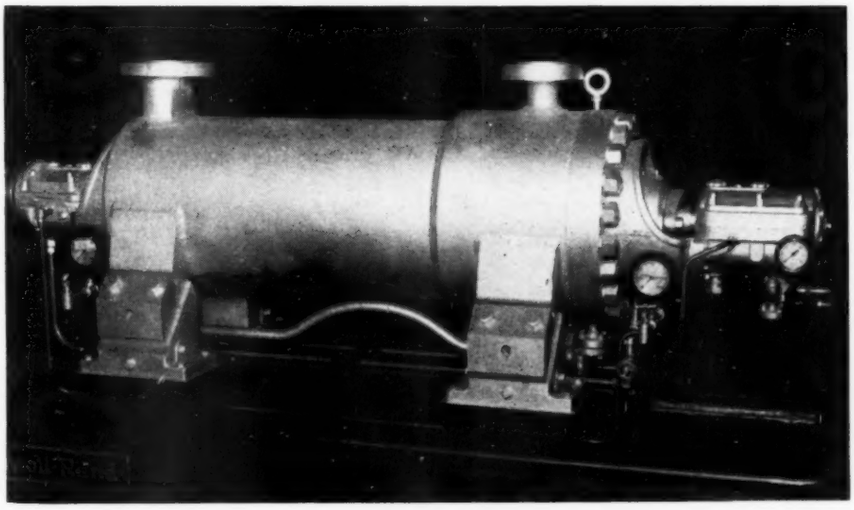


Fig. 10

by a live steam line, as the phenol solidifies at 105°F.

Cast iron is excellent material for the impeller and would also serve in the casing, but here again a cracked casing is too serious a possibility. Moreover, carbon steel will not do, nor will the alloy steels ordinarily used; 4 to 6 percent chrome and 13 percent chrome do not have reasonable resistance, but 18/8 is fairly satisfactory. Certain very high nickel chromium steels seem to have complete resistance to attack. A typical alloy contains 19 percent CR, 23 percent Ni, 3 percent Mo, and 3 percent Si. Iron gaskets are satisfactory, whereas the aluminum gaskets normally used have no resistance at all. Packing already developed works well, but must not contain any aluminum.

It was mentioned earlier that applications still existed for the type of pump originally designed to recycle hot oil in thermal cracking plants. One such application is for charge and quench pumps in thermal polymerization plants. The charge pumps must handle volumes from 500 to 1000 gal. per min. against extremely high heads, say 8,000-10,000 ft. The liquid is very light, less than 0.5 sp. gr., and is pumped at atmospheric temperature. Many stages (12-16) are required to develop the head, and the long pump resulting must be built with great accuracy. The packing boxes present another problem, and mechanical sealing devices are useful here. (Fig. 10).

The quench pump service resembles the conventional hot oil recycling service except that the temperature is lower (400-450°F.) and the suction and discharge pressures are higher. The only new metallurgical problems have to do with the materials used in internal parts having running fits in the long charge pumps, and various combinations of ferrous metals with special bronze companion parts have been successful. In some cases, parallel operation of two charge pumps is necessary and this means that a thorough study must be made of the entire pump head-capacity curve to insure stable operation at all points.

Another application for these high-pressure barrel type pumps is for handling lean oil in high-pressure absorp-

Fig. 11

tion plants in distillate fields. Capacities range up to 1200-1300 gal. per min. and discharge pressures from 1400 to 2000 lb. The oil temperature is 85-90° F. and there are no new structural, metallurgical, or packing problems, as the service is not especially severe. The remainder of the pump services in these plants are those normally encountered in conventional low-pressure absorption plants. (Fig. 11).

It is a little early to discuss the pumps required for continuous catalytic cracking, butadiene, styrene, hydroformer, and other new plants. Generally speaking, pressures are low, although temperatures are still high, and no new or

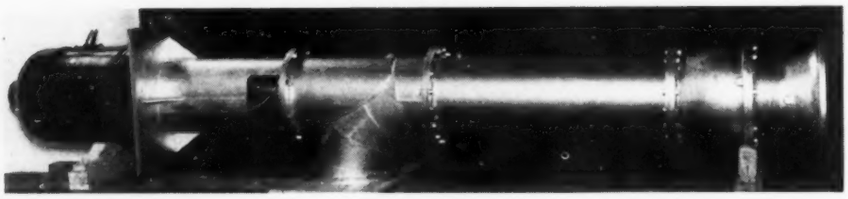


Fig. 12

startling pump developments have been required. In about a year, this phase of pump application will repay investigation.

The addition of so many new facilities has used up available cooling water

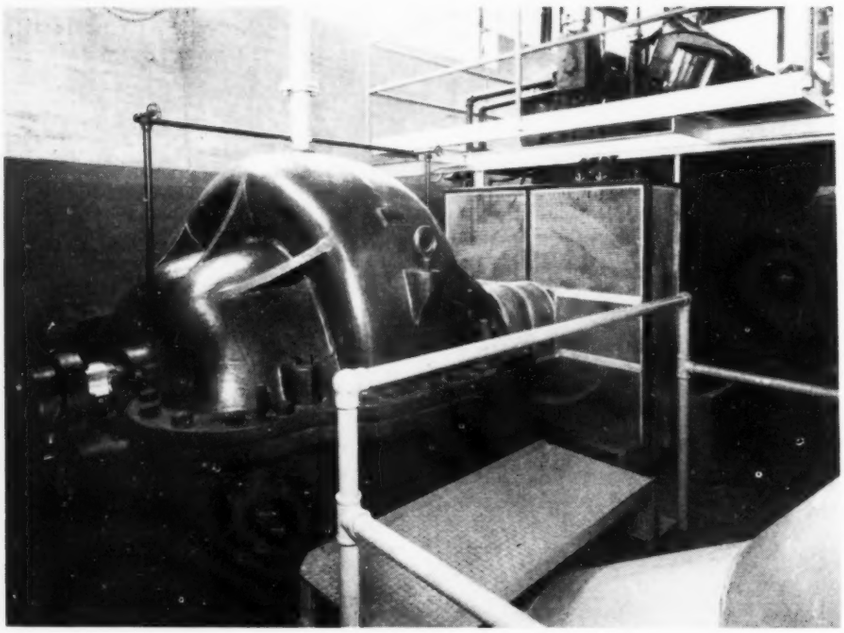


Fig. 13

supplies in many large refineries, and new sources have been developed. (Fig. 12). Occasionally, the water has to be obtained from sources remote from the plant, pumped to storage basins, conducted through channels to the refinery and there boosted up to plant pressure. New cooling towers up to 100,000 gal. per min. have been required and the necessary pumps require large amounts of power. Often electric power and steam are not available in sufficient amounts, and many gas engines have been installed to drive pumps. (Fig. 13). In fact, this has become rather common practice, although there has been a rush to install additional boilers and generators. The turbo generators used generally exhaust to high back pressure, providing steam for the various pressure levels required for power and processing needs. These boiler installations require feed pumps, for pressures ranging from 400 to 900 lb. (Fig. 14). As a matter of

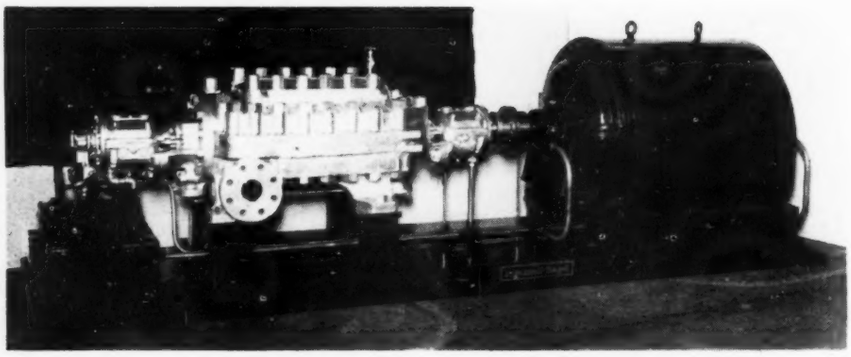


Fig. 14

interest in passing, some boiler feed pumps for industrial use in the Mid-Continent area were designed for 1600-lb. pressure and will be installed this summer, but the plant is not a refinery.

This paper is not complete, but may serve as a framework upon which may be hung the great mass of data that will unquestionably be collected during the next period of operating, rather than building, of these new refinery plants.

☆☆☆

Efficient Burning of Refinery Fuels*

By
ROBERT REED
John Zink Company

THE refinery today is either blessed or cursed with a very great variety of fuels, some of which may be burned with very little fuss or bother whereas others require much more thought and careful operation. In general, it may be said that firing with gas is much to be preferred and many plants have enough gaseous fuel available to operate all units without resorting to other types of fuel. Others, for some time, have been supplementing their gas supply with liquid fuels and in such a plant, unless it is carefully operated, efficiency is apt to go by the boards.

At this time, due to regulation from government agencies regarding the quantities of the various products that may be made, the refinery fuel picture is due for some drastic changes. Some plants that have never used liquid fuel will have to begin to burn some of their products as a disposal medium. Others will be confronted with different problems, but it is not our intention to attempt to point out the process changes required to meet regulations. It is our particular mission to be of all the help we can to you in burning your fuel to the best possible advantage.

Refinery fuels are as follows:

Gas—(1) natural gas, (2) process gas.

Liquid — (1) pitch, (2) slop oils, (3) cracking cycle stocks (gas oil), (4) residuums from cracking and topping, (5) naphthas and gasoline, (6) blends of 4 and 5, and (7) sludge.

Liquid and gaseous fuels are burned in radically different manners, as you know; so to avoid confusion we shall discuss their burning separately. There are, however, certain points of similarity in oil and gas burners that should be covered at this time.

A burner is nothing more than a device designed to permit air to flow through it into the furnace to provide oxygen for burning the fuel. Satisfactory burning of fuel requires turbulence to mix quickly the fuel stream with the air stream; and, as there are many schools of thought as to just how the turbulence should be obtained, we have many makes of burners. All gas burners are based on the eight basic designs, each of which has characteristics that are typical, and the same thing may be said of oil burner design that follows two basic types.

It should be pointed out that, in our opinion, there is no such thing as one "best" burner to the exclusion of all others. No burner is ever better than its application and, as burners conform to type, as pointed out, no major miracles of performance may be expected of any given type. The burners may be performing perfectly as they have been designed to perform and still be quite unsatisfactory from the standpoint of operation and performance.

The number and size of burners to deliver any given duty is determined chiefly by the amount of draft or subatmospheric pressure existing in the furnace to be fired. The disposition of heating surfaces in the furnace and the amount of free combustion volume that is available must also be considered. The type of burner to be used is determined by the fuel to be burned, the pressure at which the fuel is available and the condition of the fuel as delivered to the burners. Frequently we are asked, "What is the maximum capacity of this burner?" We are compelled to ask, "At what draft?" This is necessary because, for instance, one particular type of burner is good for 10,000,000 B.t.u. per hr. when the draft is 0.10 in. w.c., but at 0.5 in. w.c. draft the burner would deliver more than 21,500,000 B.t.u. per hr. The burner would, therefore, be drilled and designed for the duty according to the available draft.

Before fuel can be burned it must be in the gaseous state; so, as gas meets this requirement perfectly, a gas burner is simply a device intended to produce a complete and rapid mixture of gas and air. The greatest rapidity and completeness of mixture produces minimum flame with either fuel. With an oil burner it is first necessary to convert the oil to a vapor before mixture with air and burning may occur.

All refinery fuels as mentioned are composed of carbon and hydrogen that burn to produce CO_2 and H_2O, as they combine with the oxygen of the air in the process of burning. The chemistry of combustion is quite complex, and although most authorities accept the Hydroxylation theory, in which the hydrocarbons are converted to alcohols and aldehydes then into CO_2 and H_2O in a number of steps, it is not our intention to offer the theory as being absolutely correct, despite considerable evidence in support of it. We are, however, sure that the end products of combustion are CO_2 and H_2O.

Hydrocarbon fuels require air for combustion in inverse ratio to their H/C ratio by weight. Natural gas, having a high H/C ratio, requires the least air per cu. ft. Refinery gas of say a 0.9 sp. gr. (air equals 1.0) has an H/C ratio that is much lower, and therefore more air per cu. ft. of gas is required. This seems to build up into a vicious circle in which the use of heavier fuels requires larger and larger burners; but, fortunately, as the H/C ratio goes down, the heating value of the gas goes up so that a burner of a given size, provided with a given draft, will provide sufficient air for the same heat release with any hydrocarbon fuel. To put it differently, a burner that is capable of delivering 5,000,000 B.t.u. per hr., using natural gas for fuel, will deliver the same duty when using oil for fuel.

Excess air, or air delivered through the burner in excess of that required to burn the fuel, may be either a very useful tool or a very great hindrance in the operation of furnaces. It is very useful in that it provides a cooling medium for certain parts of the furnace or for all of the furnace; it provides extra volume of flue gas to flow over convection surfaces and increase the amount of excess air heat transferred there; through regulation of the amount of excess air, heat duty may be shifted from the radiant to the convection sections of heaters and back again at the discretion of the operator; flame may be suppressed by excess air and dangerous impingement of flame on heating surfaces may be avoided.

On the other hand, large volumes of excess air may act as a definite hindrance because the larger volume of air, discharged from the stack at high temperature, results in tremendous heat loss and lowered efficiency; an increase in the volume of excess air tends to raise the stack temperature to further hinder efficient operation; due to the presence of large quantities of O_2, oxidation of tubes and metal surfaces in the furnace is greatly accelerated; the heat transfer "pattern" is upset and excessive over-load may be placed on certain tubes in the furnace.

It is to be seen, therefore, that as excess air can do much good and also can do much that is bad, a proper middle ground in its use must be chosen and held to rigidly, if the furnace is to perform at its best in all respects.

When a furnace is designed, the designer considers all the elements entering into the manner in which the heat is to be transferred and the general re-

*Presented before Western Petroleum Refiners Association, Shreveport, Louisiana, February 12, 1943.

quirements of the job to be done. Having done this, he considers the maximum amount of excess air that may be used and arranges his heating surfaces accordingly. If the greater part of the heat is to be transferred in the radiant portion of the furnace, most of the transfer surface is located in the furnace itself and only a small convection or preheater section is provided. With this arrangement, he will recommend a low excess air factor, which would be from 20 to 30 percent. The more heat he wants to transfer in the convection the higher the excess air factor he will recommend. In some of the older furnaces flue gas is re-circulated over the convection tubes to maintain high transfer rates there.

So far as furnaces are concerned, there are two kinds of heat transfer. One of them is called "radiant," the other is called "convected." Radiant transfer is said to be obtained when there is, presumably, no direct contact between the source of heat and the object to which heat is being transferred. Radiant heat does not follow currents and is not influenced by flow of gases between the radiant and the absorbing body. It is, as the name would imply, transferred by radiation; and in order for radiant transfer to exist, there must be a completely unobstructed path between the radiant and the absorbing masses. A mass begins to radiate heat to surrounding mass or masses when its temperature becomes higher than its surroundings, and the amount of heat transferred depends upon a number of things. These are: The mass of the radiating body, the difference in temperature in the radiant and absorptive bodies, and the plane relationship and the distance between the two bodies.

Convected heat transfer is said to be obtained when hot gases flow over transfer surfaces, and the amount of heat to be transferred in this manner is determined also by a number of variables, which are: The temperature of the gases, the mass-velocity of the gases and the condition of turbulence existing as the gases flow over the surfaces, as well as the efficiency with which proper scrubbing action is obtained.

In a furnace, it is almost impossible to determine just how much heat is transferred by radiation and how much by convection because of the flow of gases in the various portions of the furnace. Current nomenclature designates that part of the furnace in which the fuel is burned as the "radiant" section, whereas convected transfer is presumably obtained in transfer surface that cannot "see" the flames or the combustion chamber proper. This nomenclature is not strictly proper as hot gases very definitely have mass and can, therefore, dissipate their heat-content by either radiation or convection or both. Convected heat transfer data, according to designing engineers, is very largely empirical.

In setting up the amount of radiant transfer to be obtained from any furnace, the designer bases his design on the excess air factor, not only because he may control furnace temperatures, etc., with excess air, but because the amount of radiant heat to be taken will vary with the CO_2 and H_2O content of the flue gas, with richer concentrations of them increasing the amount of radiation and vice versa. When the excess air is low, we have, of course, considerable CO_2 and H_2O in the flue gas.

The efficiency of a furnace is governed by the excess-air factor, the stack temperature, and the air leakage into the furnace at various points. It is, of course, true that various process conditions, such as the turbulence of flow of the medium to which the heat is being transferred, also enter into the picture; but these may be considered as outside the combustion field and not to be dealt with by us at this time. All three of the factors governing efficiency may be controlled by the careful operator.

We are frequently asked for information regarding what is the minimum excess air factor at which a furnace may be operated, and are compelled to give highly generalized answers to avoid being asked to accept the blame for badly upset process conditions or perhaps severe damage to furnaces and transfer surfaces. We do this because each furnace and fuel system is a law unto itself and must be operated accordingly. In general, it may be said that the limit on the reduction of excess air is the flame condition existing in the furnace. If the flames are very short and crisp and if the Orsat shows the presence of excessive quantities of air in the flue gas in a sample taken *in the furnace proper*, not in the duct or stack, the volume of air for combustion may be reduced. Further reduction may be taken if, along with constant checking with the Orsat to avoid running into a deficiency of air, the flames as produced by the burners remain short and clear. If reduction of air for combustion produces long flame or flame impingement on any heat transfer surface, the reduction of air should be discontinued and, in fact, more air admitted to shorten the flame and stop the impingement. If this work is being done in the average refinery that is using process gas, the reduction of excess air should be made with the heaviest gas that is to be burned at any time as fuel while the reduction is being made.

In the average refinery, the fuel may swing in heating value from 1400 B. t.u. per cu. ft. to more than 1800 B. t.u. per cu. ft. on the process gas supply; and where such conditions prevail, it is obviously necessary to establish minimum excess air while using the higher heating value fuel. When a furnace is being fired with oil, this precaution need not be observed as there is very little difference in the lengths of flames as made by either light or heavy oil when properly burned.

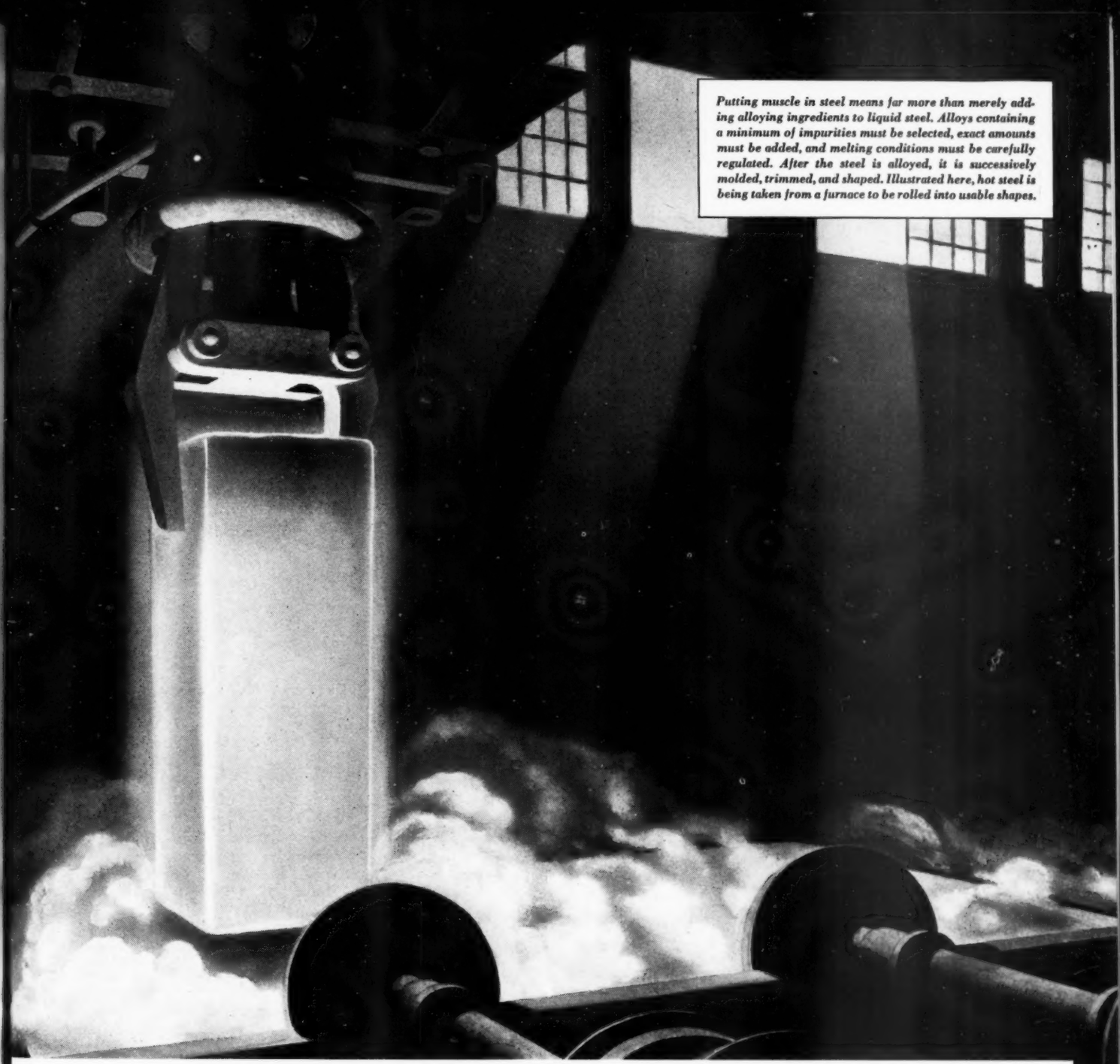
Flue gas analysis with any standard Orsat will enable the operator to determine the percentage of excess air present in any furnace, and for this reason, the Orsat is one of the most valuable tools in the maintenance of efficient operation. If the solutions are fresh and proper technique is followed, the Orsat will give a true picture of combustion conditions; but, like all good tools, the Orsat is very capable of giving an erroneous picture when it is asked to do something for which it is not designed, as is quite frequently the case.

At best, an Orsat is nothing more than an instrument designed to show the percentage by volume of CO_2, O_2, and CO present in flue gas. It will not show the water-vapor resulting from the burning of hydrogen, and it also has no provision for showing the intermediate products of combustion such as alcohols and aldehydes. We can say truthfully that we have never found CO in a flue gas sample. A number of combustion men say the same thing, others insist they have, at extremely rare intervals, found minute concentrations of CO, but, as the concentrations were so minute, it is highly questionable whether their findings were correct or the indication came as a result of faulty Orsat technique.

It is not at all to be disputed that the Orsat, provided with reasonably fresh solutions, will give a true picture of the concentrations of the gases it is designed to check in the sample to be checked. A number of sources of error exist in the manner of taking the sample and also in the manner of interpreting results obtained.

Samples of flue gas should always be taken directly from the furnace in which the fuel is being burned at a point in the furnace where it is evident that combustion is complete. Samples taken from stack or breeching will almost invariably include air leakage, which not only dilutes the sample to make the CO_2 concentration seem low, but also adds O_2 to further confuse excess air determination.

It is pointed out that indications of the presence of CO are subject to question despite the fact that the furnace may be actually running short of air. Unburned fuel, especially gas and oil, will appear either as smoke or free carbon or in the form of aldehydes. The



Putting muscle in steel means far more than merely adding alloying ingredients to liquid steel. Alloys containing a minimum of impurities must be selected, exact amounts must be added, and melting conditions must be carefully regulated. After the steel is alloyed, it is successively molded, trimmed, and shaped. Illustrated here, hot steel is being taken from a furnace to be rolled into usable shapes.

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But the stainless steels are only one great contribution of chromium. This element has also helped to provide hard, shock-resistant armor plate and armor-piercing projectiles; long-wearing engine valves; strong, tough gears, tools, ball bearings, car trucks, shafts, springs, and dies; and hundreds of other improved articles.

ELECTRO METALLURGICAL COMPANY, a Unit of UCC, does not make steel of any kind. But this Unit has for over thirty-five years carried on intensive and continuous research and development with ferro-alloys and alloying metals used in steel-making. These include chromium, manganese, silicon, vanadium, tungsten, zirconium, columbium, and calcium.

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Orsat makes no provision for indicating the concentrations of these products, so the operator has only one alternative when he suspects a furnace of being short of air. He should check one sample, and if he is suspicious of the results, he should then open the damper a little, or otherwise admit more air for combustion, and again check the flue gas. If the increase in air flow results in a lowered CO_2 reading, then it is highly probable that the first reading was essentially correct, but if an increase in air delivers a higher CO_2, then the furnace was, in all probability, short of air for combustion. He should continue to increase the air supply until such time as a further increase shows a reduction in the CO_2 reading. No CO_2 reading should be presumed to be correct unless at least three samples have given the same indication with a variation of not more than 0.2 percent.

When burning process gas in the refinery, it is well, especially if some of the gas is residual from catalytic processes, to be on the lookout for free hydrogen in the gas. The hydrogen burns to H_2O, which does not show on the Orsat. Therefore, where appreciable quantities of hydrogen are present in the gas, a fairly low CO_2 reading may still be indicative of good excess air conditions. If free hydrogen is present in the gas, excess air data may be arrived at from the theoretical ultimate CO_2 of the gas being burned or through the use of charts based on the H/C ratio by weight of the gas. With the chart, the weight of the free hydrogen should be added to the hydrogen content of the hydrocarbon fuel and a corrected H/C ratio obtained for reading from the chart.

Some refinery gases run as much as 25 percent free hydrogen and, as an example, a mixture of 75 percent ethane and 25 percent hydrogen may be considered. The specific gravity of this mixture would be 0.767 (air, 1.0) and its ultimate CO_2 would be 12.38 percent. If the hydrogen were not present in a hydrocarbon gas of the same specific gravity, the ultimate CO_2 would be 12.72 percent. In a heat balance such a difference would make a very respectable error creep into calculations, and it should be guarded against in relatively close work.

Although, as we have pointed out, it is difficult for us to make any definite assertion regarding just what excess air should be for the best conditions, we think that fair averages throughout the country would be about as follows: Oil heaters fired with gas, 25 to 40 percent; oil heaters fired with oil, 40 to 60 percent; boilers without water-walls when gas fired, 10 to 20 percent, and when oil fired, 40 to 60 percent; boilers with water-walls to protect the refractory when gas fired, 10 to 20 percent, and when oil fired, 15 to 30 percent. These figures are to be considered averages and as such may not fit your conditions at all.

With new burner design, heat releases per cu. ft. of free combustion volume have sky-rocketed. Not so long ago heater design was based on 7500 B.t.u. per cu. ft. Now some heaters run as high as 40,000 B.t.u. per cu. ft., but such instances are very exceptional and should not be used without extreme discretion as to design of the heater and the maximum transfer rates that may be taken. Even at this time 15,000 B.t.u. per cu. ft. of combustion volume needs deep consideration.

Maximum transfer rates per sq. ft. of transfer area seem to be determined more on the basis of "how much can we get through without losing tubes," than on any cut and dried procedure. We know of oil heater transfer rates that exceed 20,000 B.t.u. per sq. ft. in long service without tube failure, but it is probable that each heater or boiler is a law unto itself and should be operated in a manner particularly suited to it.

The element that probably does more to limit what may be done with any furnace is the amount of flame produced by the burners. So long as there is no flame impingement on heating surface and so long as tubes stand up well, the operator may look to the possibility of increasing throughput, but if the reverse is true, he has reached and possibly passed the critical point. It is almost a universal practice with refiners to get at least 140 percent of design and more if possible. Fortunately furnace designers and burner men are aware of this habit and usually provide for it.

To disqualify ourselves further as experts, we shall say that as a result of our work with combustion we are firmly convinced that combustion is an art, not a science, and it is usually the man who has the most experience who is able to produce the best results in any furnace. We figure that there are at least one hundred laws that govern combustion and it is asking too much of anyone to expect him to provide a proper answer for all of them, because the conditions he must meet are subject to so much variation without notice. As an example of this, we cite an instance in our experience where burners were designed and delivered to burn 800 B.t.u. gas but when the fuel arrived at the burners it was a standard 1750 B.t.u. refinery gas. It is not hard to imagine the confusion that existed when the burners were "lit-off" for operation. There was a veritable round-robin of, "Who's to blame?" But in the end experience prevailed, and the burners were made to perform satisfactorily.

We have taken your time for this generalized discussion because in it we have provided answers for problems we are continually asked to meet. From it, you may, we hope, derive some measure of assistance.

To deal with fuels and burners specifically, suppose we first think about oil burners and oil as fuel. The "ideal fuel oil" is either a topped residuum or a cracked residuum or a blend of the two ranging in A.P.I. gravity from 8 to 20 and delivered to the burners at a temperature sufficient to maintain a viscosity of 250 seconds Saybolt Universal. This temperature may probably be in the range between 150° and 200° F. according to the fuel, with heavier fuels requiring higher temperatures. This is, of course, to provide fuel for steam atomization. Pressure atomization requires different conditions.

Such a fuel is rarely seen in the refinery nowadays, as the market demands every drop of it, and the refiner who must burn liquid fuel finds it necessary to burn what is left after the market has been satisfied or at least to the best of his ability to satisfy it. Therein lies a very serious problem with which we shall try to deal.

At this time, in refineries, there are almost no pressure or "mechanical" oil burners in use and steam atomization is used instead. It should be pointed out that "atomization" as applied to oil burners is a misnomer, as the oil is not broken up into atoms at all but is rather broken up into a fine mist that may readily be converted into a vapor for mixture with air in preparation for burning. An oil burner then is a device designed to break the fuel up into a mist.

There are, essentially, two types of oil burners and the distinction between them lies in the manner of getting steam and oil together for atomization. The two types are known as the "inside-mix" and the "outside-mix" steam atomizing oil burners. In the former, the steam and oil come together inside the body of the burner, whereas in the latter mixture occurs outside the body of the burner. Inside mix burners are more satisfactory for refinery service because they use much less steam for atomization and because the shape of the flame from the burner may be regulated to suit any particular furnace proportions or conditions.

In general, it may be said that an inside-mix burner works by first foaming the oil under pressure inside the burner body and then discharging the foam through either drilled ports or through a slot, according to the flame shape produced. The foam, upon emerging into the furnace atmosphere, bursts at once into millions of tiny droplets, which are converted to a vapor by the heat of

the flame and can, therefore, burn very readily. In order for the burner to work well, it is absolutely necessary for this foaming action to take place and here the type of fuel used begins to become very important, for some fuels foam easily and make a foam that is quite stable but other fuels may not do so well in this respect.

Bunker C grade fuels are excellent for burning because they foam easily and the foam as made is quite stable. The lighter the fuel is the more difficulty may be expected in burning, because as the A.P.I. gravity goes up the foam condition becomes worse. Gas oils are very hard to burn satisfactorily. Fuel oil naphtha and gasoline blends may be burned with fair satisfaction and in many places low octane number naphthas are being burned without any mixture with heavier oil.

If it is necessary to burn very light oil, blends, or for that matter naphtha, changes must be made in oil burner design to take care of the change in the foaming characteristics of the fuel. Higher pressure must be maintained in the burner body to get satisfactory burning; and in order to meet this condition, it is necessary for both atomization steam and oil to be delivered at suitable pressure to assure flow against the higher body pressure. If the fuel oil supply pressure ran, say, 40 lb. with heavy fuel, it will probably be necessary to deliver a naphtha or a light gas oil to the burner at, say, 125 lb. The steam pressure for atomization should not be less than 150 lb.; and if it is possible, there should be some superheat on the steam.

The pressure inside the burner may be raised by reducing the discharge area in the tip until suitable conditions are obtained. This will probably require the purchase of new tips, which your manufacturer can supply. You should tell him just what type of fuel you plan to burn and he will refer to his experience to give you properly drilled or milled tips. As the tip apertures will be relatively small, it is always a very good idea to deliver the oil through a strainer the mesh of which is markedly less than the size of the ports in the tip. In this manner frequent plugging, due to scale and other foreign matter, may be avoided. The strainer is particularly recommended when lighter fuel is to be pumped through lines that formerly delivered heavier oil.

Steam for atomization should, invariably, be as dry as it is possible to get it. Nothing quite so handicaps an oil burner as does wet steam. Lines should be well insulated and a trap should be installed as close to the burner steam header as possible. It is even wise to have a bleed-valve in the header to drain condensate continuously so that it will not get into the burners.

Oil burner troubles and their probable causes are as follows:

Sparkey fire: (1) Wet steam; (2) suspended matter in the oil; (3) improper tip design for the duty being handled by the burner; (4) foreign matter inside the burner or in the tip apertures.

Long smoky fire: (1) Improper tip design; (2) shortage of air for combustion; (3) not enough steam for atomization.

Failure of ignition: (1) Improper tip design for the duty being handled; (2) too low an included angle on the flame, which is also tip design; (3) too much steam for atomization; (4) failure of fuel supply pressure; (5) firing valve stoppage; (6) wet steam or slugs of condensate from the steam lines.

When oil burner flames are dazzlingly white, it is probable that too much excess air is being allowed to enter the furnace, and when oil burner flames are fluttery, it is probable that too much steam is being used. The properly operated oil burner makes a flame that is yellow-white, perfectly steady and quite fluffy. Puffing in the furnace may be caused either by poor tip design, tip stoppage, or shortage of air, which all adds up to poor mixture of air and fuel or at least an insufficient mixture thereof.

We are frequently asked about automatic control for oil burners, and here again we have a difficult question to answer. Within certain limits partial automatic control may be obtained, but we do not know of a single case where wide ranges of heat duties are being satisfactorily handled with automatic oil-firing control. We do not say that such installations do not exist but we do say that we do not know of them.

Where oil firing is controlled remotely by loading and unloading an air controlled valve and where the oil burners operate in conjunction with constantly burning gas pilots to assure maintenance of ignition on the oil burners, a modulation range of about 10 percent may be taken without great risk, but a greater range of modulation would require individual burner adjustment by the fireman.

The burning of sludges is a problem usually given a very wide berth by burner men, and we certainly are no exception to this rule. Some success has been obtained through the use of very small cooling tower spray nozzles to which the sludge is delivered at high pressure. The whirling action produced by the spray nozzles, in combination with high pressure of delivery, breaks the sludge up into a fine spray that burns very well. Steam atomizing sludge burners do not last well because the water of the steam combined with the acid of the sludge produces a highly corrosive condition that will, at times, completely destroy a burner in a matter of hours.

Slop oils may be burned in much the same manner as the lighter oils, and the use of a strainer is very highly recommended for the removal of foreign matter from the oil.

In the burning of lighter oils and naphthas particular attention should be paid to the condition of the fuel lines and valves for, with these fuels, leaks may be very dangerous and should be guarded against. If normal precautions are observed, operation will be completely safe.

In general, it may be said of burning oil that operators who have never had to use it as fuel dread its use, because they have heard so much about the difficulty to be encountered in firing with oil. It is true that oil burning requires much closer firing control than would be necessary with gas, as automatic control is either impossible or very difficult to obtain. The fireman can no longer take his ease throughout his shift, and for this reason it is logical to expect some personnel problems in shifting from burning gas to burning a liquid fuel. Despite all the handicaps to be met and overcome in the matter of control and personnel problems, many

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heaters and boilers are being very satisfactorily and very efficiently fired with oil, and it is logical to presume that such conditions may be transferred to your plant.

Gas Burner Designs

Gas burner designs number in the hundreds, and time and space will not permit us to deal with each of them. We shall, rather, say we know of only eight basic gas burner designs, each of which has characteristics of operation that are completely typical. In accounting for all the versions of each of the basic designs, we can say only that burner men must have salient features in their particular version of any design in order to have "convincers" to offer in sales talks. As a matter of fact, the purchase of burners resolves itself more or less into calling in all the burner men and listening to their stories. After a selection has been made, the buyer should offer suitable propitiation to his particular god of luck because, as we pointed out, combustion is an art and definitely not a science.

Most gas burner design is based on air register features, which is another way of saying different means of obtaining turbulence of mixture with quickest mixtures producing the shortest flames for any given duty. The fuel delivery means may be either one of two types, however, which are: Premix, in which a portion of the air for combustion is drawn into a mixing tube by the gas and mixed therewith before being discharged into the combustion zone for burning; non-premix, in which raw gas is discharged directly into the combustion zone.

In the premix type of burner very short flame is normally expected for reasonable heat duties up to a maximum of 15,000,000 B.t.u. per hr., but it is by no means to be concluded that non-premix burners are not capable of producing short flame. If the heat duty per burner is to exceed 15,000,000 B. t.u. per hr., common practice is to use a non-premix type of burner. Any type of gas may be burned with either fuel delivery means with some exceptions.

If the gas to be burned is very dirty or very wet or if the H_2S content is high, a premix type will serve best because usually the gas is discharged from a single large orifice situated at some distance from the combustion zone. This orifice will remain clear and unobstructed by coke, gum, or corrosion for long periods; whereas with a non-premix type, much trouble with orifice plugging is normally to be expected. Plugged orifices result in decreased heat availability, which may cause serious process hindrance, if not a shutdown.

In burning gas, we have found that if a burner can be operated at high gas pressure, which is to be taken as 25 lb. per sq. in., regardless of the types of gas being burned, short flame and high efficiency may be expected, almost regardless, too, of burner design. This is particularly true of premix gas burners but is also true of non-premix burners. In the latter, because of the smaller orifices that must be used to limit the flow of gas into the combustion zone, still greater trouble with orifice plugging is almost sure to occur. It is necessary to choose a happy medium between improved combustion conditions and time-out to clean burner orifices. This last is not true of a premix burner.

We would, in fact, go so far as to say that if you are now operating burners with, say, 6- to 8-lb. gas pressure and have more pressure available, much improvement in operation may be obtained by re-drilling the gas limiting orifices of the burners to operate at higher pressure. A change from an operating pressure of 6 lb. to an operating pressure of 25 lb. will produce very marked improvement. You might ask your burner man how to go about re-drilling your burners for higher pressure if you are not completely sure of the correct procedure or orifice sizes to use.

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Capital Flow and Capital Formation in the Petroleum Industry, 1934-1941*

By JOSEPH E. POGUE and FREDERICK G. CONQUERON

Department of Petroleum Economics, The Chase National Bank, New York, New York

THE purpose of this paper is to show the flow of capital in the petroleum industry for the 8-year period 1934 to 1941, inclusive, outlining its movements into the various divisions of the business, the sources from which the capital was derived, and the final investment subdivided by functions.

The method adopted in this analysis is to construct, from financial reports and other published data supplemented by confidential information, a series of combined statements for 30 oil companies.† This list is sufficiently comprehensive to be representative of the industry as a whole. The 30 companies in 1941 produced 52.5 percent of the domestic output of crude petroleum and ran to stills 79.9 percent of the nation's total crude oil processed; and in 1938 sold 85.1 percent of the gasoline consumed in the United States.

The financial summaries apply predominantly to the domestic oil business, although it has not been possible to segregate and exclude investments in foreign assets of several companies. The reader, however, may make a mental adjustment for this necessary lack of homogeneity by noting that 9.8 percent of the gross investment, and 8.2 percent of the net investment, in fixed capital assets at the close of 1941 cover facilities outside the United States.

Other studies of this general character have been made by Koch[1] and by Gill and Weatherby,[2] whereas investment data have been compiled by the American Petroleum Institute and others.[3]

The outstanding conclusion to be drawn from this study is that the petroleum industry in the eight-year period preceding our entry into the present world war was financially self-reliant, providing for its growth almost entirely from capital charges and net profits. The data presented in this paper should also prove useful to oil companies as constituting norms against which individual performance and divergence can be measured.

Capital Expenditures

The flow of capital into fixed assets in the various segments of the oil business is shown in Table 1 and Fig. 1 for the eight years ending with 1941. The total amount invested by 30 oil companies was 5275 million dollars.‡ During this period the annual fluctuations in the size of the stream varied closely with the price of crude oil (Fig. 1), which confirms the thesis that one of the most important functions of price is to regulate the flow of capital. As an average for the period, 60 percent of the funds invested in fixed capital assets went into the producing branch, while 40 percent was expended in all other branches. If the eight-year period is separated into two equal parts, it will be found that the capital flow into the production division in comparison with the rest of the divisions was greater in the first half than in the second, as shown in Table 2.

The increase of investments in the transportation and refining segments of the industry in the four years 1938 to 1941 is accounted for principally by

*Presented before American Institute of Mining and Metallurgical Engineers, New York, New York, February, 1943.

†These companies are: Amerada Petroleum Corporation, Atlantic Refining Company, Barnsdall Oil Company, Consolidated Oil Corporation, Continental Oil Company, Gulf Oil Corporation, Houston Oil Company, Lion Oil Refining Company, Louisiana Land and Exploration Company, Mid-Continent Petroleum Corporation, Ohio Oil Company, Pacific Western Oil Corporation, Phillips Petroleum Company, Plymouth Oil Company, Pure Oil Company, Richfield Oil Company, Seaboard Oil Company, Shell Union Oil Corporation, Skelly Oil Company, Socony-Vacuum Oil Company, Standard Oil Company of California, Standard Oil Company (Indiana), Standard Oil Company (New Jersey), Standard Oil Company (Ohio), Sun Oil Company, The Texas Company, Texas Gulf Products Company, Texas Pacific Coal and Oil Company, Tide Water Associated Oil Company, and Union Oil Company of California.

[1] A. R. Koch: The Flow of Funds Through Selected Large Petroleum Companies, 1921-39 (based on 11 oil companies). Nat. Bur. Econ. Research (Sept. 14, 1940).

[2] J. D. Gill and J. S. Weatherby: The Petroleum Industry's Investment in the United States. A.I.M.E. Paper, Feb. 12, 1942. See also L. J. Logan: *Oil Weekly* (Aug. 17, 1942) 14-16, 35-36; and H. E. Rose: *World Petroleum* (Nov. 1942) 22-25.

[3] Facts and Figures, Amer. Petr. Inst., 1937, 1941. See also V. B. Guthrie: *Nat. Petr. News* (Feb. 5, 1936) 41-44.

‡The figure given does not include investments in and advances to nonconsolidated subsidiaries and affiliated companies made by the 30 oil companies. These amounts cannot be compiled precisely but probably aggregated 200 to 250 million dollars gross.

TABLE 1
Trend of gross expenditures by 30 oil companies for properties, plant, and equipment classified by divisions and facilities for the eight-year period 1934-1941*

Divisions and facilities	1934	1935	1936	1937	1938	1939	1940	1941	Total 1934–1941
	Thousands of dollars								
Leases, wells and equipment	268,665	333,363	375,997	576,714	382,795	348,351	345,375	409,109	3,040,369
Crude-oil purchasing and marketing	5,478	4,465	9,101	12,005	6,511	8,857	6,454	6,287	59,158
Natural-gasoline plants	29	10	118	592	611	388	564	409	2,721
Natural gas	10,050	4,157	7,295	15,862	5,314	6,454	10,244	4,900	64,276
Total production division	284,222	341,995	392,511	605,173	395,231	364,050	362,637	420,705	3,166,524
Crude-oil pipe lines	14,260	16,784	31,943	43,661	19,238	37,798	35,026	57,182	255,892
Product pipe lines	50	2,451	3,102	5,847	2,153	5,106	3,444	23,890	46,043
Marine	9,804	7,349	36,132	27,228	32,119	38,219	46,072	69,726	266,649
Tank cars	253	427	559	889	193	244	776	398	3,739
Motor transport	766	822	875	1,203	733	739	814	1,560	7,512
Total transportation division	25,133	27,833	72,611	78,828	54,436	82,106	86,132	152,756	579,835
Refining division	64,219	52,866	74,072	112,344	108,982	117,209	103,705	113,578	746,975
Marketing division	81,378	78,996	87,104	112,201	93,243	83,211	91,259	113,119	740,511
Administrative	661	590	1,130	1,328	1,027	2,384	554	1,987	9,661
Mining	4	46	237	31	109	84	22	136	669
Shipbuilding	191	118	424	441	978	549	1,406	718	4,825
Unallocated	-301	6,116	-3,768	5,776	3,250	6,552	3,427	4,681	25,733
Total all other	555	6,870	-1,977	7,576	5,364	9,569	5,409	7,522	40,888
Grand total	455,507	508,560	624,321	916,122	657,256	656,145	649,142	807,680	5,274,733

Divisions	1934	1935	1936	1937	1938	1939	1940	1941	Total 1934–1941
	Percentage of total								
Production	62.4	67.2	62.9	66.1	60.1	55.5	55.9	52.1	60.0
Transportation	5.5	5.5	11.6	8.6	8.3	12.5	13.3	18.9	11.0
Refining	14.1	10.4	11.9	12.3	16.6	17.9	16.0	14.1	14.2
Marketing	17.9	15.5	13.9	12.2	14.2	12.7	14.0	14.0	14.0
All other	0.1	1.4	-0.3	0.8	0.8	1.4	0.8	0.9	0.8
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

*Summarization is based on the combined expenditures of the companies and their consolidated subsidiaries for facilities in the United States and foreign countries, and excludes expenditures by these companies for investments in and advances to nonconsolidated subsidiaries and affiliated companies.

Expenditures represent gross additions to fixed asset accounts (per Annual Report to Stockholders, Form 10-K submitted to S.E.C. and other sources); and also include intangible development costs of producing wells and dry holes, and lease purchase costs charged to income account, if data were reported.

TABLE 2
Capital expenditures of 30 oil companies, 1934-1941, by divisions

Divisions	1934–1937	1938–1941	1934–1941
	Percentage of total		
Production	64.8	55.7	60.0
Transportation	8.2	13.6	11.0
Refining	12.1	16.0	14.2
Marketing	14.4	13.7	14.0
All other	0.5	1.0	0.8
Total	100.0	100.0	100.0

the discovery of the Illinois fields requiring substantial outlays for crude-oil pipe-line facilities; by additions to tanker fleet; by the construction of product pipe-line facilities in the southeastern states; and by the installation of catalytic units for the manfacture of high-octane gasoline. Expenditures for marketing facilities reached a new high in 1941, primarily as a result of construction of retail service stations. The decline in expenditures in the producing division correlated with the recession in crude-oil prices and the general deflation in the economic cycle following the boom year of 1937.

Over the eight-year period, the total capital invested in leases, wells and equipment was 3040 million dollars.** During this same period, 9.5 billion bbl. of crude oil were produced in the United States. Assuming that the 1941 ratio held for the entire period, the 30 companies under consideration produced 52.5 percent of the total, or 5.0 billion bbl. If we assume further that 90 percent of the investment was allocated to domestic oil fields, the average investment per barrel of production was 55 cents. In other words, during the eight years, 1934-1941, production of crude oil in the United States increased 55 percent, and for every barrel recovered 55 cents was invested in producing facilities. This relationship indicates the importance of reinvestment in maintaining crude-oil supply.

**This figure does not include substantial sums expended for maintaining land, geological and geophysical departments and for lease rentals on undeveloped acreage.

Sources of Capital

It was shown in Table 1 that 30 oil companies in the eight years invested 5275 million dollars in the maintenance and expansion of the oil business. What were the sources of this capital? Table 3 indicates that 3874 million dollars, or 73 percent, was derived from "capital extinguishments;" that is, deductions from income set aside as return of capital and therefore available for reinvestment. In Table 3 is shown the breakdown of these charges into their various accounts, of which depreciation represents 69 percent.

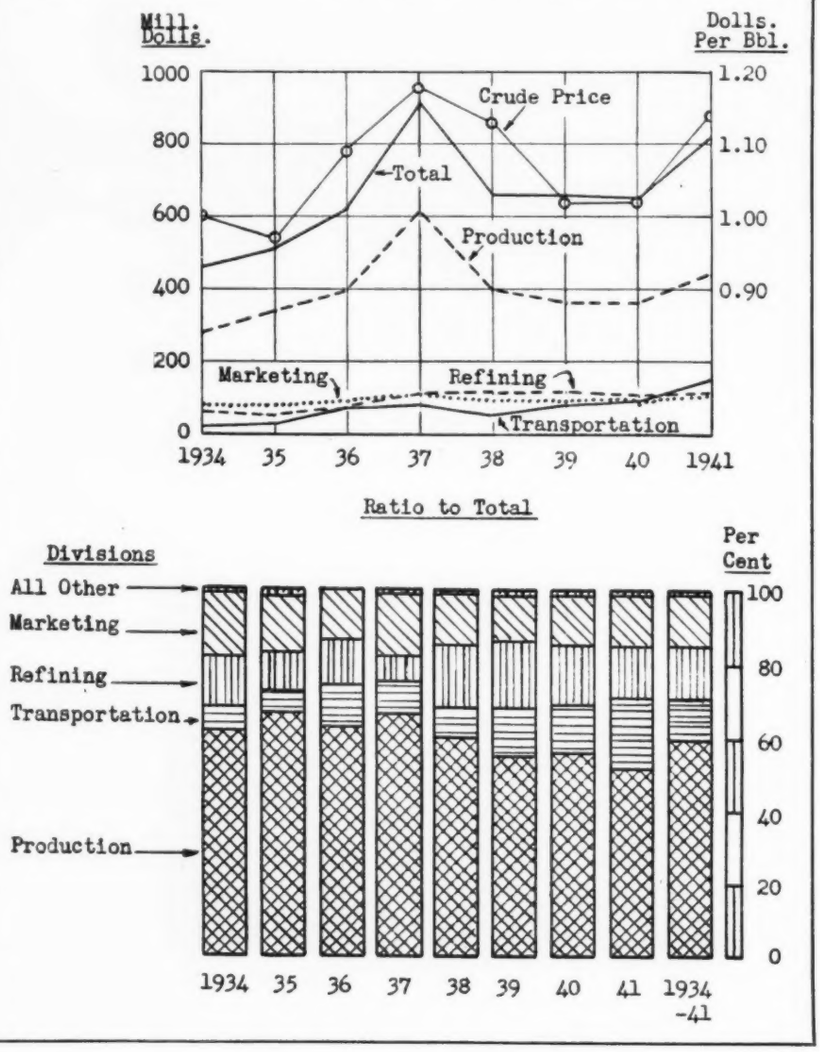
Table 4 and Fig. 2 reveal how closely the petroleum industry came to supporting itself capitalwise. The 30 oil companies in eight years reported net income of 2925 million dollars, which, with the addition of 3874 millions for capital extinguishments and 160 millions for other charges, indicates a total cash production of 6959 million dollars; which was sufficient to support capital expenditures of 5275 millions and dividends of 1617 millions, with a margin left over of 67 millions. It should be noted also that dividends for the whole period represented 55 percent of net income—a very conservative proportion — and only 23 percent of cash production. Therefore, out of every dollar of cash produced, 77 cents was ploughed back into the business.

As a matter of fact, the 30 oil companies during the eight pre-war years increased their consolidated funded and long-term debt by a net amount of only 190 million dollars, going from 875 millions on January 1, 1934, to 1065 millions on December 31, 1941. Table 5 shows this item along with the change in total borrowed and invested capital, which on December 31, 1941, amounted to 7417 million dollars. The turnover in the oil industry's capital is illustrated by the fact that the cash invested in fixed assets in eight years was 52 percent of the gross investment in service at the end of the period. It would appear that the oil industry must replace its capital as a whole every 15 years.

The total funded and long-term debt of the 30 oil companies at the close of 1941, amounting to 1065 millions of dollars (Table 5), was derived as follows: from the public, 55 percent; from banks, 17 percent; from insurance companies, 14 percent, and from other sources, 14 percent.

The net working capital of the 30 oil companies increased 185 million dollars over the eight-year period, as shown in Table 6, and the composite ratio of current assets to current liabilities declined from 4.89 to 3.20 between the beginning and the end of the period. Tables 5 and 6, in conjunction with Table 4, permit the sources and destinations of the capital flow to be reconciled and balanced from an accounting standpoint and Table 7 shows how this is done. The only sources of income, aside from the companies' own cash production, was 190 millions from borrowings and 73 millions from sale of common stock; and the only application of capital, aside from expenditures for plant and facilities and for dividend payments, was 50 millions for retirement of preferred stocks, 95 millions for in-

Fig. 1. Trend of gross expenditures by 30 oil companies for properties, plant and equipment classified by divisions and facilities for the eight-year period 1934-41. For data see Table 1



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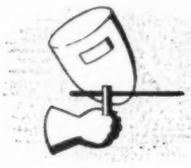

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TABLE 3

Comparison of gross expenditures for properties, plant and equipment with capital extinguishments charged to income account by 30 oil companies for the eight-year period 1934-1941

Millions of dollars

Year	Gross expenditures	Capital extinguishments	Excess expenditures over extinguishments
1934	456	422	34
1935	509	441	68
1936	624	458	166
1937	916	493	423
1938	657	504	153
1939	656	502	154
1940	649	523	126
1941	808	531	277
Total 1934-1941	5,275	3,874	1,401

Analysis of capital extinguishments

	Millions of dollars
Depreciation	2,664
Depletion and lease amortization	241
Intangible development costs	235
Amortization of intangible development costs	168
Dry holes and wells abandoned	154
Canceled leases and lease purchases	169
Property retirements	186
All other	57
Total	3,874

TABLE 4

Estimated cash income from earnings of 30 oil companies available for dividends and capital expenditures during the eight-year period, 1934-1941

Millions of dollars

Year	Reported net income	Capital extinguishments*	Amortization of intangible assets	Provision for war losses and contingencies	Estimated cash income from operations	Preferred and common dividends paid	Balance available for capital expenditures	Capital expenditures†	Balance available for other purposes
1934	156	422	3	1	582	128	454	456	− 2
1935	253	441	3	5	702	119	583	509	74
1936	415	458	3	8	884	233	651	624	27
1937	573	493	4	6	1,076	289	787	916*	−129*
1938	300	504	3	5	812	199	613	657	− 44
1939	321	502	4	19	846	189	657	656	1
1940	377	523	3	24	927	209	718	649	69
1941	530	531	3	66	1,130	251	879	808	71
Total 1934-1941	2,925	3,874	26	134	6,959	1,617	5,342	5,275	67

*Includes charges to income account for depreciation, depletion, amortization, property retirements, canceled leases and intangible development costs.

†Represents gross additions to fixed asset accounts plus intangible development costs of producing wells and dry holes and lease purchase costs charged to income account.

*Includes $109,616,000 in respect of acquisition by International Petroleum (consolidated subsidiary of S. O. New Jersey) of an undivided one-half interest in the oil rights in Venezuela owned by Mene Grande Oil (consolidated subsidiary of Gulf Oil); $75,000,000 of purchase price represented by noninterest-bearing purchase obligation maturing as follows: 1938, $26,820,000; 1939, $25,000,000 and balance of $23,180,000 on or before Dec. 15, 1945. In 1938 International Petroleum sold an undivided one-half interest in these rights to Royal Dutch for $54,808,000.

TABLE 5

Change in borrowed and invested capital employed by 30 oil companies during the eight-year period from January 1, 1934, to December 31, 1941

	1/1/34	12/31/41	Change
	Millions of dollars		
Funded and long-term debt*	875	1,065*	+190
Preferred stock†	239	189	— 50
Common stock	3,624	3,439	—185
Surplus	1,793	2,457	+664
Minority interest	333	267	— 66
Total borrowed and invested capital	6,864	7,417	+553
	1/1/34	12/31/41	Change
	Percentage of total		
Funded and long-term debt	12.7	14.4	+1.7
Preferred stock	3.5	2.5	—1.0
Common stock	52.8	46.4	—6.4
Surplus	26.1	33.1	+7.0
Minority interest	4.9	3.6	—1.3
Total borrowed and invested capital	100.0	100.0	

*Excludes current debt due within one year. Includes advances (millions of dollars) owing to Standard-Vacuum by:

	1/1/34	12/31/41
Socony-Vacuum	24,582	9,660
S.O. New Jersey		9,176
Total	24,582	18,836

†Accrued unpaid dividends were as follows:

1/1/34	$12,728,000
12/31/41	2,505,000

*Borrowed from:

	Millions of dollars
Public	581
Insurance companies	149
Banks	186
All other	149
Total	1,065

TABLE 6

Change in net working capital position of 30 oil companies during the eight-year period from January 1, 1934, to December 31, 1941

Millions of dollars

	1/1/34	12/31/41	Change
Cash	370	647	+277
Marketable securities	246	359	+113
Inventories of crude oil, refined products and merchandise	857	855	— 2
Inventory of materials and supplies	116	191	+ 75
Receivables and other items	398	515	+117
Total current assets	1,987	2,567	+580
Bank loans, purchase obligations and other borrowings	51	83	+ 32
Payables, accruals and other items	355	718	+363
Total current liabilities	406	801	+395
Net working capital	1,581	1,766	+185
Ratio of current assets to current liabilities	4.89	3.20	—1.69

TABLE 7

Summary of net working capital available to 30 oil companies for financing capital expenditures during the eight-year period from January 1, 1934, to December 31, 1941

Millions of dollars

Net working capital 1/1/34	1,581
Add:	
1. Cash income from operations	6,959*
2. Funded debt and long-term borrowings	190
3. Proceeds from sale of common stock	73
Subtotal	8,803
Less:	
1. Preferred and common dividends paid	1,617
2. Preferred stock retired	50
3. Investment in securities of other companies, elimination of foreign consolidated subsidiaries and other items	95
Balance available for capital expenditures	7,041
Less: capital expenditures	5,275
Net working capital 12/31/41	1,766

*Basis of computation:

	Millions of dollars
Reported net income	2,925
Add: Capital extinguishments	3,874
Amortization of intangible assets	26
Provision for war losses and contingencies	134
Cash income from operations	6,959

TABLE 8

Change in gross investment in properties, plant, and equipment of 30 oil companies during the eight-year period from January 1, 1934, to December 31, 1941

Millions of dollars

Gross investment 1/1/34		8,281
Add:		
Expenditures (gross additions)	5,117	
Fixed assets of companies not consolidated in prior years	149	
All other (includes revaluation of properties, interdepartmental transfers and sundry charges.)	38	5,304
Subtotal		13,585
Less:		
Retirements and sales	2,447	
Fixed assets of foreign subsidiaries and branches eliminated from consolidation	460	
Other credits*	505	3,412
Gross investment 12/31/41		10,173
Net increase		1,892

*Includes:

	Millions of dollars
Four public utility natural-gas companies eliminated from consolidation (S.O. New Jersey)	185
Five subsidiaries operating in Far East transferred to Bahrein Petroleum, and pipe-line subsidiary (Texas-New Mexico Pipe Line) eliminated from consolidation (Texas Company)	35
Premiums on investments in capital stocks of subsidiaries written off (Shell Union)	24
Appreciation of proven oil properties written off (Union Oil)	91
Subsidiaries eliminated from consolidation, interdepartmental transfers, depreciation and depletion charges credited to fixed asset accounts and sundry credits	170
Total	505

vestments in other companies and other purposes, and an increase of 185 millions in working capital.

Cumulative Investment

The foregoing sections have dealt with the flow of capital and how it was financed. The accumulated effects of these processes will now be analyzed; that is, the resultant investment in fixed capital assets broken down into its functional parts.

Table 8 reveals the growth in the gross investment in fixed capital assets of the 30 oil companies, from 8281 mil-

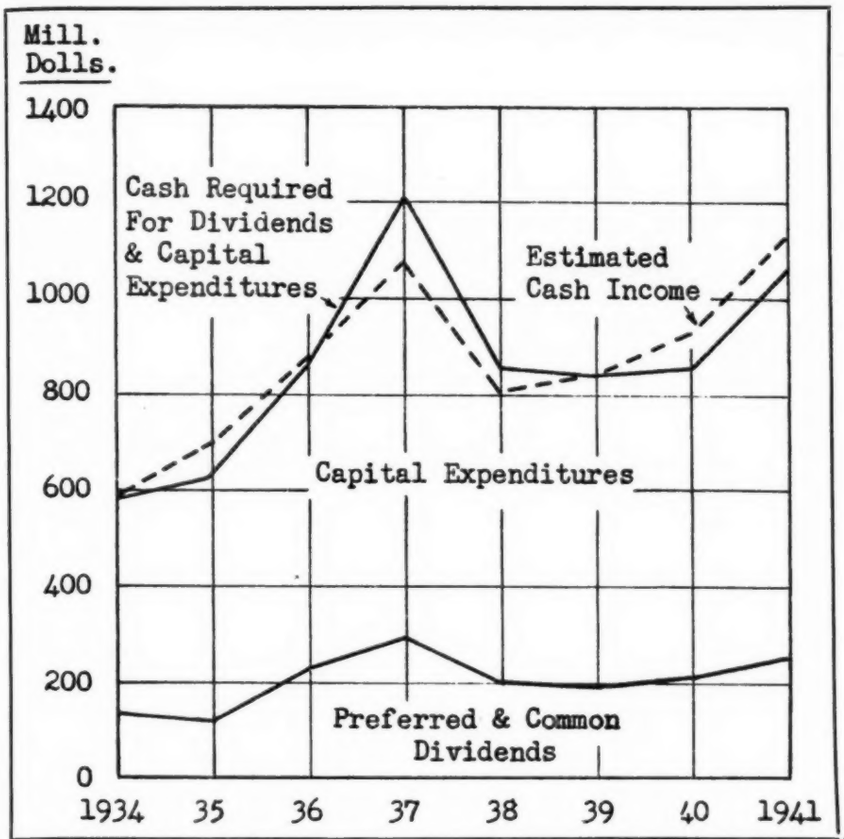


Fig. 2. Estimated cash income from earnings of 30 oil companies available for dividends and capital expenditures during the eight-year period 1934-1941. For data see Table 4

lion dollars at the beginning of 1934 to 10,173 million dollars at the close of 1941. Table 9 gives both the gross and net investment at the end of 1941, classified by divisions and facilities of the business. (See also Fig. 3.) For example, of the total gross investment, production accounts for 49.0 percent; transportation, 15.2 percent; refining, 18.7 percent; marketing, 15.1, and all other, 2.0 percent.

A view of the invested capital from a different point of view is given in Table 10 and Fig. 4, which show the borrowed and invested capital employed by 30 oil companies, classified according to its financial character. The small proportion of capital in the form of debt is significant, ranging from 12.8 percent at the close of 1933 to 14.4 percent at the close of 1941. Roughly, 80 percent of the capital employed by the group of oil companies under review is in the form of common stock and surplus; surplus being about two-thirds the amount of the common

Fig. 3. Gross and net investment of 30 oil companies in properties, plant and equipment classified by divisions and facilities at December 31, 1941. For data see Table 9

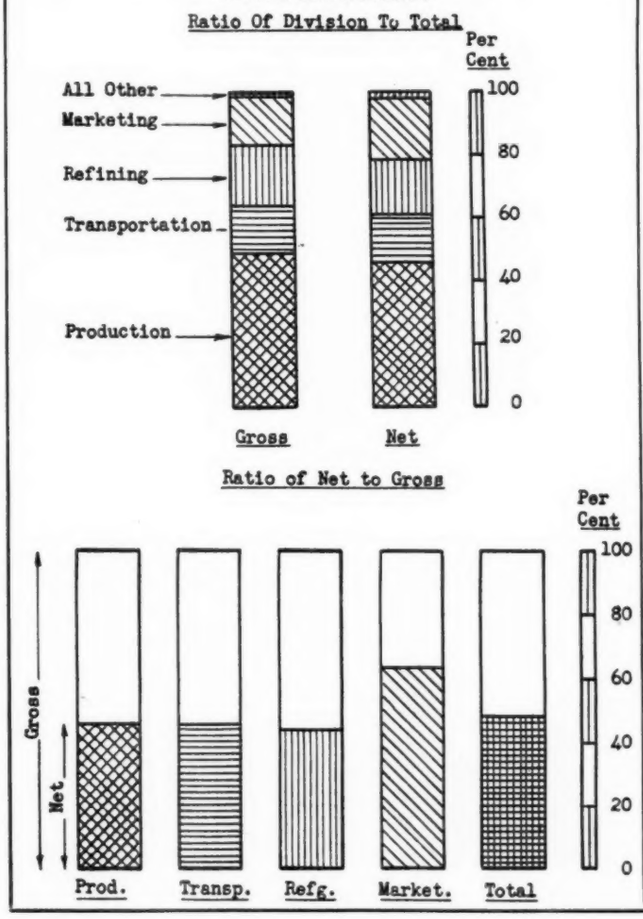


Fig. 4. Borrowed and invested capital employed by oil companies during the eight-year period December 31, 1933 to 1941. For data see Table 10

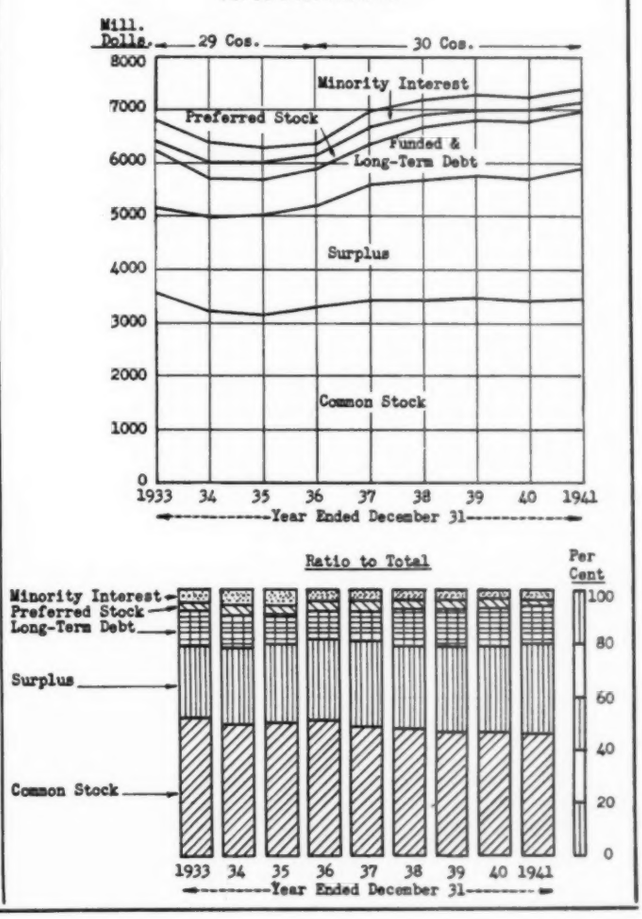


TABLE 9

Summary of gross and net investment of 30 oil companies in properties, plant, and equipment classified by divisions and facilities at December 31, 1941*

Divisions and facilities	Gross investment	Accumulated reserves	Net investment
	Millions of dollars		
Leases, wells and equipment	4,738	2,568	2,170
Crude-oil purchasing and marketing	25	10	15
Natural-gasoline plants	152	95	57
Natural gas	75	42	33
Total production division	4,990	2,715	2,275
Crude-oil pipe lines	875	498	377
Product pipe lines	80	19	61
Marine	537	290	247
Tank cars	38	26	12
Motor transport	14	8	6
Total transportation division	1,544	841	703
Refining division	1,898	1,058	840
Marketing division	1,540	570	970
Administrative	53	18	35
Mining	1	1	
Shipbuilding	17	10	7
Unallocated	130	57	73
Total all other	201	86	115
Grand total	10,173	5,270	4,903

Divisions	Gross	Net	Ratio of net to gross
	Percentage of total investment		Percent
Production	49.0	46.4	45.6
Transportation	15.2	14.3	45.5
Refining	18.7	17.1	44.3
Marketing	15.1	19.8	63.0
All other	2.0	2.4	57.2
Total	100.0	100.0	48.2

*Summarization is based on the combined investment in fixed (capital) assets per books as reported by the companies and their consolidated subsidiaries, and excludes investment in and advances to non-consolidated subsidiaries and affiliated companies operating in the United States and foreign countries.

Total investment includes approximately $1000 million (gross) and $400 million (net) covering facilities located in foreign countries.

TABLE 11

Distribution of borrowed and invested capital, 30 oil companies, close of 1941

	Millions of dollars	Percentage of total
Properties, plant and equipment (after deducting accumulated reserves)	4,903	66.1
Net quick assets	1,766	23.8
Investment in foreign subsidiaries, not consolidated	261	3.5
Investment in affiliated and other companies	721	9.7
Subtotal	7,651	103.1
Less: Reserves for contingencies and other purposes	234	3.1
Total borrowed and invested capital employed	7,417	100.0

TABLE 13

Rate of return on invested capital of 29 oil companies versus group of over 1100 manufacturing companies, by years, 1934-1941

Year	29 oil companies	Over 1100 manufacturing companies	Difference
	Percent		
1934	2.9	4.3	— 1.4
1935	4.9	6.7	— 1.8
1936	7.7	10.4	— 2.7
1937	10.1	10.8	— 0.7
1938	5.1	4.8	+ 0.3
1939	5.4	8.5	— 3.1
1940	6.3	10.3	— 4.0
1941	8.8	12.4	— 3.6
Average	6.4	8.7	— 2.3

TABLE 12

Percentage return on invested capital by 29 oil companies during the eight-year period 1934-1941

Year	9 solely producing companies			4 companies with production in excess of refinery requirements			16 companies with production less than refinery requirements			Total 29 companies		
	Average invested capital*	Net income†	Return	Average invested capital*	Net income†	Return	Average invested capital*	Net income†	Return	Average invested capital*	Net income†	Return
	Millions of dollars		Percent	Millions of dollars		Percent	Millions of dollars		Percent	Millions of dollars		Percent
1934	131	6	4.7	401	17	4.2	4,868	135	2.8	5,400	158	2.9
1935	136	9	6.5	394	30	7.7	4,720	217	4.6	5,250	256	4.9
1936	137	14	10.1	398	40	10.1	4,850	360	7.4	5,385	414	7.7
1937	139	16	11.4	421	57	13.4	5,103	498	9.8	5,663	571	10.1
1938	140	15	10.5	426	21	5.0	5,282	262	5.0	5,848	298	5.1
1939	139	11	8.0	422	20	4.7	5,337	287	5.4	5,898	318	5.4
1940	137	9	6.8	423	28	6.6	5,350	336	6.3	5,920	373	6.3
1941	135	15	11.1	429	50	11.5	5,388	462	8.6	5,952	527	8.8
Yearly average 1934-1941	136	12	8.7	414	33	7.9	5,113	320	6.3	5,663	365	6.4

*Invested capital represents the average of the book value of outstanding preferred and common stocks and consolidated surplus accounts at the beginning and end of each year.

†Net income is after deducting all charges and represents earnings available for preferred and common dividends.

TABLE 10

Borrowed and invested capital employed by oil companies during the eight-year period from December 31, 1933 to 1941

Year ending	Number of companies	Funded and long-term debt	Preferred stock	Common stock	Surplus	Minority interest	Total
	Millions of dollars						
12/31/33	29	866	239	3,550	1,793	333	6,781
12/31/34	29	764	237	3,187	1,793	393	6,374
12/31/35	29	685	233	3,143	1,906	362	6,329
12/31/36	29	671	246	3,290	1,951	273	6,431
12/31/37	30	776	269	3,430	2,217	280	6,972
12/31/38	30	983	244	3,440	2,247	272	7,186
12/31/39	30	1,025	244	3,457	2,315	274	7,315
12/31/40	30	1,035	235	3,425	2,317	257	7,269
12/31/41	30	1,095	189	3,439	2,457	267	7,417
	Percentage of total						
12/31/33	29	12.8	3.5	52.3	26.5	4.9	100.0
12/31/34	29	12.0	3.7	50.0	28.1	6.2	100.0
12/31/35	29	10.8	3.7	49.7	30.1	5.7	100.0
12/31/36	29	10.4	3.8	51.2	30.3	4.3	100.0
12/31/37	30	11.1	3.9	49.2	31.8	4.0	100.0
12/31/38	30	13.7	3.4	47.9	31.2	3.8	100.0
12/31/39	30	14.0	3.3	47.3	31.6	3.8	100.0
12/31/40	30	14.2	3.2	47.1	31.9	3.6	100.0
12/31/41	30	14.4	2.5	46.4	33.1	3.6	100.0

stock—a reflection again of a conservative dividend policy.

A reconciliation of the funds invested in fixed assets, as shown in Table 9, with the total borrowed and invested capital, as shown in Table 10, may be summarized as shown in Table 11.

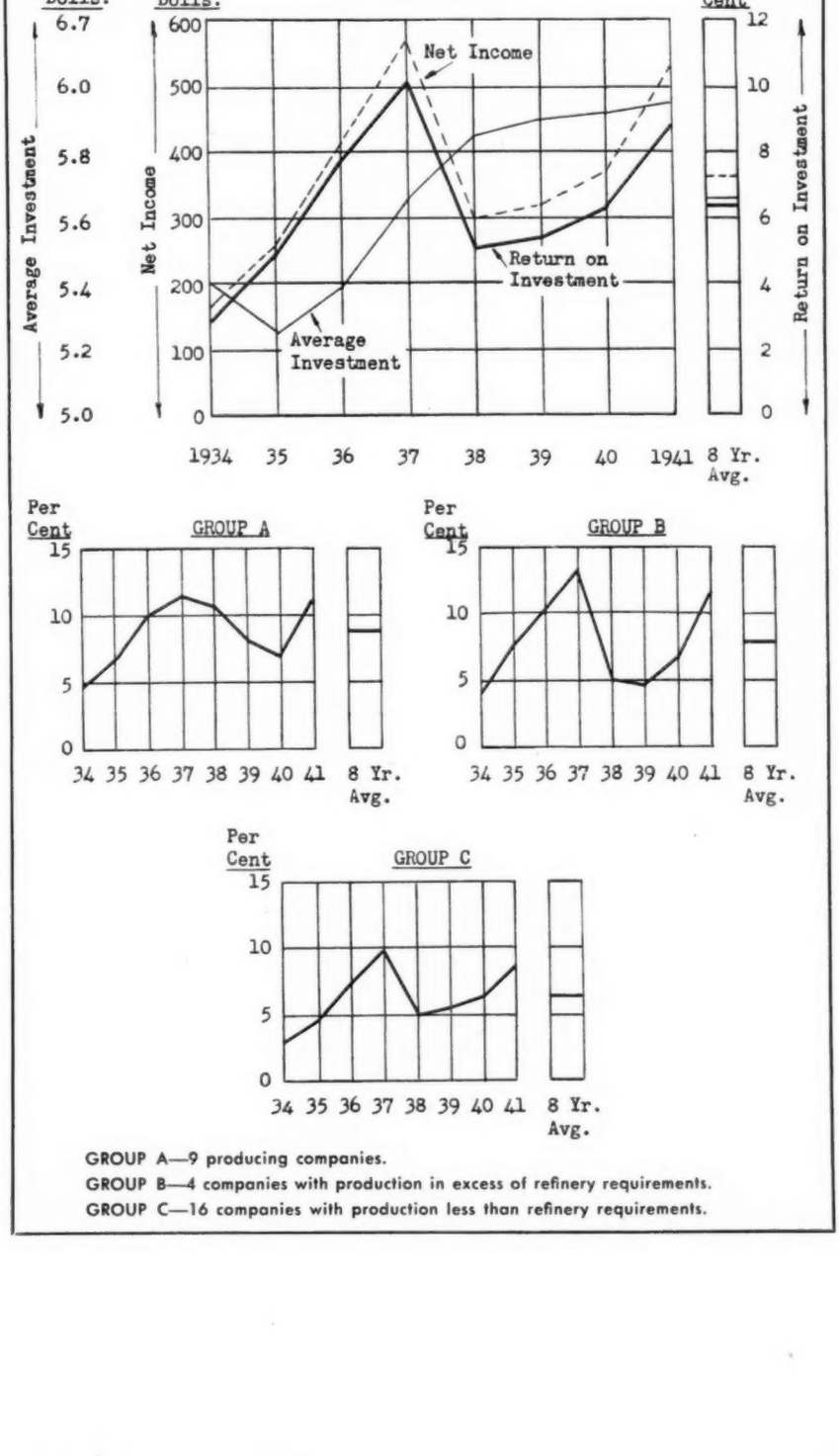
Return on Investment

It may be of further interest to compute the rate of return on invested capital for the group of companies. The calculations have been made for 29 oil companies† and the method employed was to calculate the ratio of reported net income available for preferred and common stocks to the average of the net worth at the beginning and end of each year. The results of these calculations are shown in Table 12 and Fig. 5. The average rate of return for the eight-year period was 6.4 percent, with

†One of the 30 companies was excluded because of the lack of adequate information for the earlier years. The invested capital of this company on Dec. 31, 1941, was 1.4 percent of the group total.

a range of 2.9 percent in 1934 to 10.1 percent in 1937. The results were also subdivided for the eight-year period into three groups according to the degree of integration; solely producing companies showed an average return of 8.7 percent; companies with crude production in excess of refinery requirements, 7.9 percent, and companies with refinery requirements in excess of crude production, 6.3 percent. Producing companies were, accordingly, slightly more profitable than integrated companies, as should be the case because of their large requirements for venture capital.

Fig. 5. Percentage return on invested capital by 29 oil companies during the eight-year period 1934-1941. For data see Table 12



GROUP A—9 producing companies.
GROUP B—4 companies with production in excess of refinery requirements.
GROUP C—16 companies with production less than refinery requirements.

The rate of return earned by 29 oil companies for the eight years ending with 1941 is 2.3 points less than that of a group of over 1100 manufacturing companies as compiled by The National City Bank. The comparison is shown in Table 13.

Conclusions

Analysis of the financial data covering a representative group of 30 oil companies for a period of eight pre-war years, aside from constituting an economic and accounting record, leads to several broad conclusions:

1. The petroleum industry generated the capital necessary for its maintenance and expansion, thus constituting a self-reliant industry.

2. The net increase in debt was very modest and the existing ratio of debt to other forms of capital is conservative.

3. Investments in fixed capital assets increased in importance between 1934 and 1941, and current assets became less important in relationship to borrowed and invested capital.

4. Nearly two-thirds of the capital invested went into the producing branch of the industry, indicating the high cost of replacing and increasing crude-oil reserves.

5. The efficiency of capital utilization is indicated by the fact that the 30 oil companies under review increased their crude-oil production by 55 percent and their runs to stills by 52 percent between 1934 and 1941 as compared with a net expansion of 23 percent in gross fixed capital assets.

6. The gross investment in fixed capital assets of 30 oil companies on December 31, 1941, was 10,173 million dollars, divided as follows: production, 49.0 percent; transportation, 15.2 percent; refining, 18.7 percent; marketing, 15.1 percent, and all other, 2.0 percent.

7. The flow of funds exhibited cyclical variations, expenditures for capital investments fluctuating with changes in the price of crude oil.

8. The return on invested capital for 29 oil companies for eight years averaged 6.4 percent against 8.7 percent for a group of over 1100 manufacturing companies.

9. The consolidated statements here submitted point to an oil economy functioning soundly and effectively.

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